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Vice Presidency for Strategic Planning and Supervision

Guideline for seismic evaluation and rehabilitation of power supply systems

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Chapter 1

Generalities

1-Generalities

Electricity provides the energy needed for production and delivering services, light and heating, and the force needed for establishing contacts and information technology, and generally facilitates the essential deeds of today's modern societies. Earthquake is one the natural disasters which can inflict damages to such systems and cause power cut. Lack of awareness about the vulnerability level, strength and required safety, and not performing sufficient seismic rehabilitations, increases the consequences and damages resulted from earthquake, and with lack of proper bracing, the emergency conditions may lead to catastrophe and critical conditions.

1-1-Objectives

The objective of seismic evaluation and rehabilitation if power supply systems is to acknowledge their seismic safety and then minimizing the consequences resulted from earthquake on these systems and components. Maintaining the integrity and safe performance of this system ensures lack of unacceptable risks for human lives and their properties as well as the environment. The main objectives in preparing this guideline are:

- Defining and determining the general criteria of seismic vulnerability evaluation for current power supply systems which are applied nationwide uniformly and in concert with each other.
- Presenting seismic rehabilitation approaches for power supply system components to manage hazard reduction and contingent emergency and critical conditions.

1-2-Scope of application

The contents of this guideline are applicable on power supply systems including every power supply vital artery in transmission, super-distribution, and distribution sectors in different capacities and sizes (voltage levels of 400, 230, 132, and 63 kV). The contents of this guideline provides a ground to promote the engineering knowledge level in the field of seismic safety, but the responsibility for correct interpretation and application of its contents is on users. The contents of this guideline will be reviewed and revised over time and the users should use its latest updated version.

The safety evaluation against other natural and unnatural factors as well as the considerations related to them are not presented within the framework of this guideline and should be reviewed complementarily in case necessary. The necessities of the guideline are similar for both permanent and temporary installations.

1-3-Target components

The target components are divided into two major categories in this guideline:

- Stationary components including buildings, non-building structures, equipments, and non-structural components in power-plants and substations.
- Line (power transmission lines) and network (power distribution) components.

The stationary components are generally on-ground, except for some limited cases, while line and network structures are both underground/buried in some cases and on-ground in other cases. The stationary structures are essentially affected by the ground acceleration from earthquakes, while buried line and network structures receive more impacts from the ground velocity response to earthquake. Also, the stationary equipments consist include indoor and outdoor types.

Unlike buildings which their mass is nearly uniformly distributed in different floors, the stationary structures of vital arteries lack a certain mass distribution; therefore, the inertia force from earthquake is applied on their center of mass. This force is obtained from multiplying structure's weight by modified acceleration in terms of seismic factor. For some maintaining and storage structures, such as tanks (whether cylindrical or spherical containing liquids or grains with free surface or under-pressure), the inertia force resulted from earthquake is applied or distributed on the container's mass statically or dynamically on the related location, depending on the analysis method and its mathematical model. In limited cases with semi-buried structures, depending on the applied analysis method and its mathematical model (free, constrained, and semi-constrained parts), the proper loading would be performed.

The long line and network structures, whether underground or on-ground, are sensitive to their imposed relative displacement. The imposed relative displacement is converted into strain and stress in these structures. The effect of inertia is dramatically reduced from on-ground to buried line and network structures, because in buried structures the structure's behavior is practically affected by soil's behavior and its mass is quite scant and negligible relative to its surrounding soil.

The power supply components which are reviewed for seismic evaluation and rehabilitation in this guideline are presented in table (1-1).

Table 1-1: Target components of this guideline

Component's Title	Type of Component
Gas and thermal power plant	Stationary
Conversion substations	Stationary
Super-distribution aerial and buried transmission lines	Line
Dispatching	Stationary
Distribution aerial and buried substations	stationary
Distribution aerial and buried lines	Line
Office and public buildings and logistics building	Stationary
Subscribers branches	stationary

1-4-Related regulations

The regulations and codes as well as guidelines related to this collection are as follows:

- Latest revision of Iran 2800 standard, building designing against earthquakes, Ministry of Housing and Urban Development
- Instructions for seismic rehabilitation of buildings, issue #360, President deputy of strategic planning and control
- Instructions of buildings fast evaluation, issue #346, President's deputy of strategic planning and control
- Instructions of seismic vulnerability and rehabilitation of current unarmed monumental buildings, Ministry of Housing and Urban Development

- Instructions of seismic evaluation of power plants installations, issue #512, President's deputy of strategic planning and control
- Instructions of seismic evaluation of electricity substations installations, issue #513, President's deputy of strategic planning and control
- Iranian National Building Code, Ministry of Housing and Urban Development

Using other guidelines and criteria which could be needed in special projects is permissible, provided their general compliance with the contents of this guideline and satisfying the minimum criteria.

1-5-Structure of guideline

The current guideline consists of the following chapters and appendices:

Chapter one: Generalities

Chapter two: Seismic evaluation procedure

Chapter three: Seismic evaluation methods

Chapter four: Seismic rehabilitation procedure

Chapter five: seismic rehabilitation methods

Appendix 1: Classification of power supply network subscribers

Appendix two: Examples of destruction functions

In chapter two of the guideline, the general seismic evaluation procedure of power supply systems is presented. This procedure defines the seismic evaluation studies through two general sections, namely pre-evaluation and evaluation. The pre-evaluation procedure is presented in this chapter while the evaluation procedure is in the next chapter. The seismic pre-evaluation is presented in this chapter for the general seismic vulnerability prediction of components, and using this, the primary screening of vulnerable components could be performed. Also, considering the different evaluation requests based on employers' objectives, the general level of studies and outputs could be determined.

In order to perform pre-evaluation, the effective factors in evaluation are introduced in this chapter, and based on this, the evaluation level index is determined and the evaluation level is selected. Next in this chapter, based on the selected levels, the suggested titles for planning the evaluation studies and also the stages for continuing studies following the completion of pre-evaluation are presented in order to prepare the description of evaluation's necessary services.

In chapter 3, the vulnerability evaluation methods are suggested as matrices for various components in three categories, fast, qualitative, and detailed, for the different evaluation levels presented in chapter 2, following introduction of target components in a power supply system. For each method and component, the codes related to determining the methods' details are listed, while introducing the factors important in evaluation.

For fast and qualitative evaluations, the important points to consider in preparation and completion of worksheets used in this section are presented through chapter 3, according to the importance of technical control in this two methods.

The details of the detailed methods for different components, such as load combinations and calculation of seismic capacity, and acceptance criteria in addition to items mentioned in chapter 3, are a function of seismic design methods of each component, and it could be referred to the related codes presented in this chapter for each component in order to determine them.

The fourth and fifth chapters discuss the procedures and methods of rehabilitation, respectively. The rehabilitation procedure include introduction of effective factors on prioritizing the rehabilitation design presentation and rehabilitation design preparation steps. The different rehabilitation methods for different components separately and detailed are the pre-requirements for the topic of the fifth chapter of this guideline.

Chapter 2

Seismic evaluation procedure

2-1-Seismic evaluation approaches

The seismic evaluation is defined through two stages in this guideline. The first stage is the pre-evaluation which by fast examination of vital artery state, the studies level is signified while determining the need or lack of need for evaluation. Then, in the evaluation stage, the activities are defined in primary or detailed evaluations, as follows. The roadmap of seismic performance evaluation is shown in the following figure.

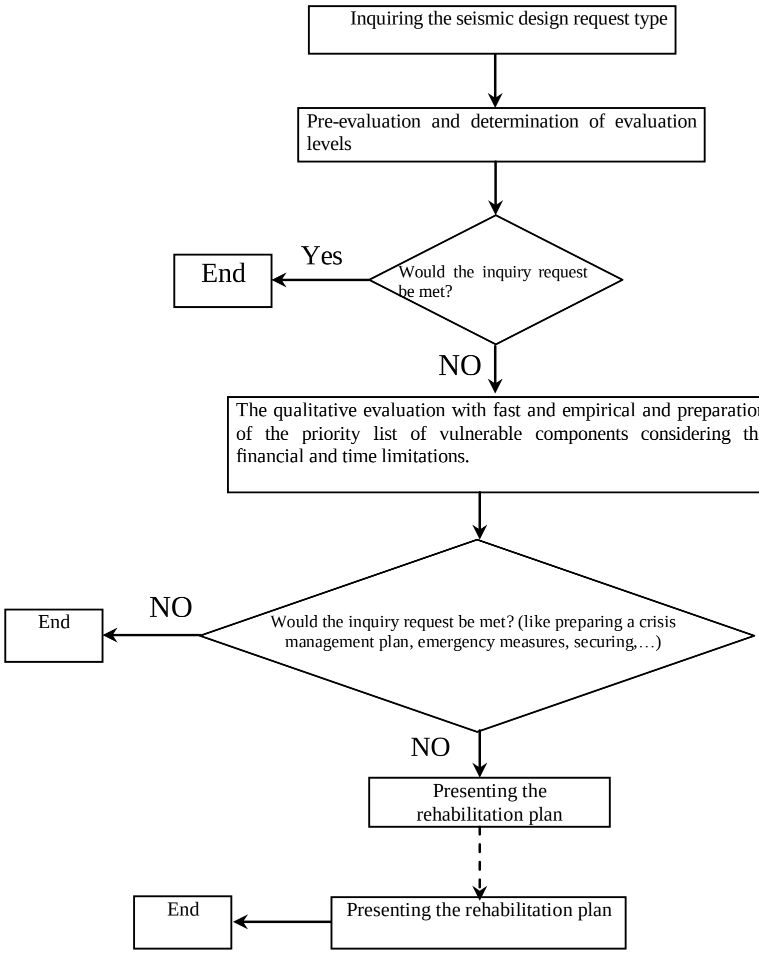


Figure 2-1: Performance evaluation road map

- The primary evaluation includes the empirical and qualitative methods. This evaluation is relatively fast and it requires the detailed evaluation in order to determine the vulnerable or safe components. Generally, the primary evaluation methods of this guideline are based on primary evaluation worksheets with qualitative or quantitative scoring.
- The detailed evaluation includes two empirical and analytic approaches. The empirical methods are based on damage mode and stats and history of damages in the past earthquakes. The analytic methods are based on modeling and numerical calculation analyses. Often, the empirical methods are used for seismic evaluation of networks with large number of components. Generally, these empirical methods are based on empirical and possibility damage diagrams of different components in different modes. More details on damage diagrams are

presented in appendix 1 of this guideline. The analytic method has also two levels. The first level is similar to simplified design methods and is mostly static-equivalent method. The second level is used for components with special conditions or more complex behavior and includes dynamic and non-linear methods.

2-2-Pre-evaluation

The system operator must be always sufficiently aware and certain about the proper seismic safety and performance of his/her installations. Otherwise, the request for performance evaluation of power installations is the submitted. The required level and details of evaluation depend on the requester's needed knowledge level. Before initiating the evaluation, the pre-evaluation stage is preformed for the following objectives which could be carried out by the operator engineer:

- Hazard's intensity identification and general vulnerability evaluation against it in order to determine the required level for detailed evaluation
- Assuring the availability of resources and sufficient, proper expertise for evaluation
- Determining the proper level of studies based on the request, available resources, and schedule.

2-2-1-Types of evaluation requests

The evaluation requests could be in one of the following three approaches:

- Technical approach (usually aimed to promote safety by performing rehabilitation practices)
- Financial approach (usually aimed for budget planning and/or capital loss, return, and risk assessments)
- Management approach (usually with goals such as crisis management planning, planning for immediate and emergency measures, increased-safety planning with software or non-rehabilitation and risk management plans)

The components which should be evaluated are largely dependent on the request and target's performance. Based on this, the director of installations should decide which components to be evaluated. The reliability in this instruction is measured based on the amount of power cuts and the duration of power cuts.

This request may not be submitted for the whole network, and be based on the crisis management priorities. In this case, the measurement of service delivery reliability initiates with the priority of more important subscribers which play more significant roles in controlling and management at the time crisis. Preparing a list and how the important subscribers in a network are selected is carried out based on the guides in appendix 1.

2-2-2-Factors effective on performance evaluation

The main factors in a performance evaluation are:

- Hazard (H)
- The seismic hazard includes primary and secondary hazards. The primary hazards are vibrations and ground intense shakes and deformation caused by them, such as liquefaction, slope slip, and faulting. The secondary hazards include explosion, fire, environmental

pollution, and likes of them which are resulted from occurrence of primary damages of earthquake.

- Vulnerability (V):
- The vulnerability includes the potential of life losses and physical damages in relation to equipments, installations, buildings, operational and control systems, environment, industrial, office, financial and business activities, security of installations, capitals, society, and cultural heritage.
- System performance (S):
- The performance of power supply vital artery during earthquake hazard is evaluated and judged based on outputs, operational objectives, safety defects, and performance disturbance. The major operational objectives of a power supply system are:
- Safety of people's and personnel's life
- Continuation of electric current and reliability on system
- Preventing damages
- Preventing environmental damages

2-2-3-Identification of seismic hazard

The primary seismic hazards including vibrations permanent ground deformations are measured based on intensity, acceleration, and ground's intense movements. The most common measurement criterion of vibrations is the peak ground acceleration (PGA) which could be obtained from zonation maps or on-site studies. In order to investigate the level of permanent ground deformations, including liquefaction, landslip, and faulting, could also be performed using the zonation maps. The information of this map is approximate and conservative, to some extent. For example, a province might be placed in the high hazard classification against earthquake, only because a small portion of this province is on instable slopes.

The seismic secondary hazards, such as explosion, fire, environmental pollution, and likes of them, should be examined case-specific and local. Table (2-1) shows the hazard levels classification criterion.

Table 2-1: Criteria used in determining the relative hazard levels (H status)

Seismic hazard level	Seismic peak acceleration range
Low (L)	PGA>0.15 g
Medium (M)	0.15g ≤ PGA≤ 0.5 g
High (H)	PGA > 0.5g

2-2-4-Seismic vulnerability identification

According the history of past earthquakes, the vulnerability potential of different power supply parts against seismic hazards is different. Table (2-2) indicates the general degree of this topic for High (H), Medium (M), and Low (H) categories. If one components or system is placed inside a building, the vulnerability of the building and component must be considered together. For example, where there is a possibility of building collapse or its emergency evacuation, the equipments inside the building are exposed to danger.

Table 2-2: Components' vulnerability degree against seismic damages (V status)

Seismic Hazards	**Vulnerability Degree**								
	Control, conservation, and communication low-voltage systems (like SCADA)	Transmission substations	Transmission lines	Transmission and communication masts and distribution post	Distribution substation	Distribution lines	Service distribution transformers	Central office, maintenance building, operation building	Computer equipments for operation and business activities
Earthquake Vibrations	M	H	L	L	M	M	M	M	M
Permanent Ground Deformations due to earthquake (faulting, liquefaction, and landslip)	L	M	H	H	M	H	M	H	L

2-2-5-Seismic performance

The seismic performance depends on the following factors:

- Intensity and amount of hazard
- Vulnerability of system of component
- Consequences caused by life or financial damages, service cut, environmental impacts, and other effects.
- Permanent redundancy amount of the evaluated system (High redundancy, redundant, or no-redundancy)
- System size

In pre-evaluation, the performance is defined by the layer index, I_L, as the product of H, V, and S:

$$I_L = H \times V \times \max\left(C_{LS}, C_{FL}, C_{SD}, C_{EI}\right) \qquad (2.1)$$

H: degree of hazard (low = 1, medium = 2, high = 3, according to table 2.1)

V: degree of vulnerability (low = 1, medium = 2, high = 3, according to table 2.2)

S: degree of system performance (maximum of CLS, CFL, CSD, and CEI)

CLS: degree of life safety consequences, varies between 1 and 3 (According to table 2.3)

CFL: degree of financial loss consequences, varies between 0.5 and 6 (According to table 2.3)

CSD: degree of service cut consequences, varies between 0.5 and 6 (According to table 2.3)

CEI: degree of environmental impacts consequences, varies between 1 and 3 (According to table 2.3)

In table (2.3) a redundancy correction factor (RC) is used to determine CFL and CSD. Indeed, using this correction factor justifies the decrease in consequences due to system redundancy.

The redundancy correction factor provides the possibility of flexibility in weighting differently some of the performance special conditions, provided the availability of the alternative resources.

For example, for one establishment, the redundancy factor might be determined equal to 2 (no-redundancy) due to lack of knowledge about a proper alternative for servicing an important subscriber. While, the subscriber himself might consider this factor equal to 0.5 due to existence of a proper alternative; therefore, the CSD could vary depending on the nature and characteristics of request and who is performing the evaluation. There are similar considerations when applying the redundancy correction factor to CFL. The redundancy correction factor is equal to 1, for normal cases.

Table 2-3: Degrees of system performance disturbance consequences (S status)

Consequence	**Intensity of Consequence**		
	Low (Normal)	**Medium (Non-critical)**	**High (Critical)**
Life safety CLS	Minimum impact on life safety; without any important or significant effect on personnel or people around facilities CLS = 1	The damage or cut could inflict injuries to personnel or people around facilities CLS = 2	The damage or cut could bring significant life threats for personnel or people around facilities CLS = 3
Financial loss CFL	No or low effects CFL = RC	The damage or power cut could inflict high financial losses, but these losses have no or low effects on facility economic status CFL = 2RC	The damage or power cut has significant effect on economic status of facility and/or a number of main subscribers CFL = 3RC
Service cut CSD	No or low effects on population under its coverage CSD = RC	Power cut: - affects a small portion of covered population (less than 10%) - lasts less than one day and has no specific effect on any important subscriber CSD = 2RC	Power cut would lead to one the following: 1) Affects a considerable portion of covered population (more than 10%) 2) Has the potential to affect a population more than 100 thousand people 3) Includes a broad area and lasts more than one day 4) Affects the performance and operation of an important and vital facility CSD = 3RC
Environmental impacts CEI	No or low effects on the environment CEI = 1	The damage or power cut might cause limited environmental impacts CEI = 2	The damage or power cut might cause large environmental damages (i.e. neutralizing its effects might take months or years) CEI = 3

RC is equal to 0.5 for high redundancy (member damages do not reduce system's performance); for medium redundancy equals to 1 (member damages reduce system's performance); and for no-redundancy is equal to 2 (the task performed by that member only and no other alternatives would do the same). The scoring system is approximate and replacing decimal values instead of 1 for low, 2 for medium, and 3 for high is not considered.

The final step in the scoring operations is to compare the layer index, IL, with a set of pre-determined ranges which defines the recommended base level for performance evaluation. Based on all the possible combinations of input parameters, the layer index could vary from 0.5 to 54. The performance evaluation base level could be determined using the ranges presented in table (2-4). The base level is used as a starting point for evaluation and later more complete evaluations could be felt. Sometimes the inquirer might request a specific level of studies based on his/her requirements.

Table 2-4: Selection of evaluation levels

Layer Index	Base Level for Performance Evaluation
$I_L \leq 6$	No need for seismic evaluation
$7 \leq I_L < 17$	Generally, the primary evaluation is sufficient (level 1)
$17 \leq I_L < 35$	Primary and detailed evaluations using empirical and common calculative methods (level 2)
$I_L \geq 35$	Primary and detailed evaluations using accurate calculative methods (level 3)

2-2-6- Evaluation studies planning

The required information for seismic evaluation and the type of studies differ based on the different seismic levels. In addition to the guides presented by the chapter's tables, also issues such as cost and schedule as well as numerous hazards must be included in planning of evaluation studies type.

Table 2-5: Hazard evaluation matrix for power supply system

Hazard/Measure		H1	H2	H3
1.1	Earthquake hazard – surface failure of fault			
1.1.1	Reviewing the regional earthquake's history and active faults hazards maps, if available	♦	♦	♦
1.1.2	Reviewing topographic maps	♦	♦	♦
1.1.3	Reviewing aerial maps, if available	♦	♦	
1.1.4	Performing identification and site visits (by an expert geologist)	♦	♦	
1.1.5	Highlighting active faults by excavating trenches	♦		
1.1.6	Estimating fault's displacements using empirical methods	♦	♦	
1.1.7	Determining fault's displacements and their occurrence possibility by excavating bores, sampling, age determination, and analysis	♦		

Hazard/Measure		H1	H2	H3
1.2	Earthquake hazard – liquefaction			
1.2.1	Reviewing documentations concerning regional vibrations (seismic-risk)	♦	♦	♦
1.2.2	Probability evaluating of earthquake hazard throughout the whole system	♦	♦	
1.2.3	Reviewing topographic maps	♦	♦	♦
1.2.4	Reviewing ground surface geological maps	♦	♦	♦
1.2.5	Reviewing the current geotechnical data	♦	♦	♦
1.2.6	Performing minimum excavation and soil boring, standard penetration tests and/or cone penetration		♦	
1.2.7	Performing extensive excavation and soil boring, standard penetration tests and/or cone penetration	♦		
1.2.8	Performing preliminary visits and site detection (desert) (by an expert geologist)	♦	♦	
1.2.9	Identifying soil mines with liquefaction potential by judgment	♦	♦	♦
1.2.10	Identifying soil mines with liquefaction potential by engineering analysis of sail data	♦	♦	
1.2.11	Estimating the amount of lateral displacement spreading by empirical methods	♦	♦	
1.2.12	Estimating the liquefaction potential using liquefaction capability maps	♦	♦	
1.2.13	Applying detailed analysis using analytical tools, estimating liquefaction possibility, and lateral displacements spreading.	♦		

Hazard/Measure		H1	H2	H3
1.3	Earthquake hazard – ground intense vibrations			
1.3.1	Reviewing documentations concerning regional vibrations (seismic-risk)	♦	♦	♦
1.3.2	Reviewing regional seismic hazards, if available	♦	♦	♦
1.3.3	Reviewing ground surface geological maps	♦	♦	♦
1.3.4	Determining and developing factors amplifying ground shakes	♦	♦	
1.3.5	Estimating levels and elevation of ground shakes using judgment and current maps	♦	♦	♦
1.3.6	Estimating levels and elevation of ground shakes using empirical methods	♦	♦	
1.3.7	Estimating levels and elevation of ground shakes using analytical methods and tools	♦		
1.3.8	Applying PSHA to the whole system	♦		

Hazard/Measure		H1	H2	H3
1.4	Earthquake hazard – landslip			
1.4.1	Reviewing geological maps of earth surface	♦	♦	♦
1.4.2	Reviewing topological maps	♦	♦	♦
1.4.3	Reviewing aerial maps, if available	♦	♦	
1.4.4	Reviewing regional precipitation maps	♦	♦	♦
1.4.5	Performing site visits and identification (desert) (by an expert geologist)	♦	♦	
1.4.6	Reviewing current regional ground shakes maps	♦	♦	♦
1.4.7	Evaluating the potential of landslip by expert judgment	♦	♦	♦
1.4.8	Evaluating the potential of landslip by slope stability maps	♦	♦	
1.4.9	Evaluating the potential of landslip by statistical or empirical analysis	♦	♦	
1.4.10	Evaluating the potential of landslip by analytical methods	♦		

Hazard/Measure		H1	H2	H3
1.5	Earthquake hazard – Tsunami			
1.5.1	Determining the location of facilities in a 20km range from shore	♦	♦	♦
1.5.2	Reviewing topographic maps of shore areas	♦	♦	♦
1.5.3	Reviewing bathymetric maps of boundary areas (close to shore)	♦	♦	
1.5.4	Reviewing records by local wave/tide gauges	♦	♦	♦
1.5.5	Estimating potential of tsunami water overflow using expert judgment	♦	♦	♦
1.5.6	Estimating potential of tsunami water overflow using judgment and evaluating the tsunami possibility sources	♦	♦	
1.5.7	Analyzing regional flooding	♦	♦	♦

Table 2-6: Vulnerability evaluation matrix

Component/Measure		V1	V2	V3
1	Damage evaluation of power system facilities			
1.2	Collecting information by interviewing facilities designers, site engineers, and executive managers. Obtaining performance evaluation (estimates, heuristic estimates), and every performance data (statistical) which should be informed about.	♦	♦	♦
1.2	Collecting information by examining the site for local conditions evaluation and information related to the total vulnerability of components.	♦	♦	
1.3	Collecting information by examining the site for parallel hazards resulted from external sources, structures, and neighboring facilities.	♦	♦	
1.4	Collecting information by reviewing maps and calculations of critical and important issues of facilities.	♦	♦	
1.5	Collecting information by visiting location and determining the installation details of critical items in facilities.	♦	♦	
1.6	Performing structural calculations for examining and determining the sufficiency of installation details of critical and important items in facilities and matching with characteristics based on performance.	♦		
1.7	Evaluation of equipments' fragility using location data, heuristic estimates, empirical data from previous events (statistical) with minimum local collected data.	♦	♦	♦
1.8	Evaluation of equipments' fragility using location data obtained from (1.2) to (1.5), more accurate and more detailed data of loads, and equipments' sufficiency, and fragility tests	♦	♦	
1.9	Evaluation of equipments' fragility using actual in-place data (according to steps (1.2) to (1.6)) and selected equipments' structural analysis results	♦		

Component/Measure		V1	V2	V3
2	Damage evaluation of critical and important buildings			
2.1	Collecting information through interviewing executive managers of facilities and maintenance personnel of building	♦	♦	♦
2.2	Determining critical performances inside buildings and damages which have defected or stopped these performances	♦	♦	♦
2.3	Paying general visits to sites for evaluation of local conditions and collecting information about buildings' general vulnerability, their contents, and each facility near them and their supports	♦	♦	
2.4	Paying general visits too sites for evaluation of parallel hazards from external sources and structures and neighboring equipments	♦	♦	
2.5	Performance evaluation of buildings and support equipments using judgment (estimates, heuristic estimates) and/or empirical data (statistical) from past events and/or using empirical evaluation of damages with minimum local collected information	♦	♦	♦
2.6	Reviewing architectural and structural maps, design calculations, foundation evaluation reports, and also past structural evaluation reports for evaluating buildings' capacity.	♦	♦	
2.7	Performing independent structural calculations for building capacity evaluation.	♦	♦	
2.8	Performing independent structural calculations for building response evaluation	♦		

Table 2-7: Performance evaluation matrix

Measure		S1	S2	S3
1	System performance evaluation			
1.1	Reviewing system maps	♦	♦	♦
1.2	Reviewing system performance against natural hazards/previous events	♦	♦	♦
1.3	System's critical performance model	♦	♦	
1.4	Matching system model on maps of various hazards (GIS performance)	♦	♦	
1.5	Estimating system's performance using expert judgment	♦	♦	♦
1.6	System analysis for limited scenarios (minimum 3)	♦	♦	
1.7	Probability analysis and system reliability	♦		

Table 2-8: Minimum necessary effort for evaluation of hazard, vulnerability, and system's performance in different levels

1 to 15 man-hour	(white)
3 to 10 man-hour	(grey)
3 to 9 man-hour	(black)

Evaluation levels of system performance			Vulnerability Evaluation V1	V2	V3
S1	Hazard evaluation	H1	(white)	(white)	(grey)
		H2	(grey)	(grey)	(grey)
		H3	(black)	(black)	(grey)
S2	Hazard evaluation	H1	(grey)	(grey)	(grey)
		H2	(grey)	(grey)	(grey)
		H3	(black)	(black)	(black)
S3	Hazard evaluation	H1	(black)	(grey)	(grey)
		H2	(black)	(black)	(grey)
		H3	(black)	(black)	(black)

2-3-Seismic Evaluation Stages

After performing pre-evaluation and determining the level of studies, it would be necessary for seismic emulation to determine the seismic vulnerability, seismic hazard, and seismic performance level of the target. These parameters, which determine the volume of necessary activities for evaluation of each component, are listed in the evaluation stages according to the following order:

1- Level of importance and system general value
2- Calculating seismic hazard of different elevations
3- Determining component/system performance levels
4- Selecting the primary seismic evaluation method
5- Determining the primary vulnerability
6- Selecting the detailed seismic evaluation method
7- Determining the detailed vulnerability

2-3-1-Determining importance of component or system

The first step in seismic evaluation is to determine the importance and role of the system in a network which is carried out according to table (2-3). After systems' classification, the subsystems and internal components are classified based on their relative importance and role in power supplying, according to table (2-9). Table (2-10) indicates how the role combination of internal components and the entire system in seismic evaluation.

Table 2-9: Classification of subsystems and internal components

Type	Definition	Effect of Damage on Performance
Main	Direct role in system performance	Power cut
Auxiliary	Support or redundancy role in system performance	Disturbance in power supplying
Subordinate	Main or support role in system performance	Unknown

Table 2-10: Determining the importance with combination of internal components and entire system

Subsystem or internal component / Entire system or set	Main	Auxiliary	Subordinate
Up	Very high	High	Medium
Middle	High	Medium	Low
Down	Medium	Low	Low

Also, the obtained importance level could be obtained as following:

1- *Very high:* inflicting damages to these components would lead to critical conditions and cause several casualties and financial losses.

2- *High:* inflicting damages to these components results in power- and service delivery-cut as well as financial losses.

3- *Medium:* inflicting damages to such components would cause disturbance in currents.

4- *Low:* inflicting damages to such components has no effect on the system.

2-3-2-Earthquake hazard level

Three earthquake hazard elevations are defined for evaluation:

- Hazard level-1: Maximum Operational earthquake (MOE)
- Hazard level-2: Maximum Design Earthquake (MDE)
- Hazard level-3: Maximum Considered/Credible Earthquake (MCE)

These hazard levels are equivalent to the following safety levels which their precise definition is presented in table (2-12) for different importance levels:

- <u>Operational safety:</u> In this level, the possible imposed damages should not create any disturbance in power supplying.
- <u>Design safety:</u> In this level, the possible imposed damages might create temporary and short-term disturbance in power supplying but should not lead to major damages, collapses, fire, explosion, network instability, and so forth.

- Safety from crisis: In this level, high operational damages might occur but no system damages should be inflicted; therefore, it is necessary to consider required measure to minimize secondary effects.

Table 2-11: earthquake seismic hazard levels

Seismic Level	Probability of emergence in 50 years (earthquake return period in years)	Safety Level
Hazard level-1 (MOE)	99.5% (75 years)	Operational safety
Hazard level-2 (MDE)	10% (475 years)	Design safety
Hazard level-3 (MCE)	2% (2475 years)	Safety from crisis

2-3-3-Performance levels of system components

The definition of performance levels based on hazard level and importance classification of vital arteries' equipments is presented in table (2-12).

Table 2-12: Definition of seismic performance levels based on earthquake hazard level and importance classification

	Seismic elevation (Performance level)		
Importance level	Earthquake hazard level-1 (operational safety)	Earthquake hazard level-2 (design safety)	Earthquake hazard level-3 (safety from crisis)
Very high	Without any damage and performance disturbance	No life damages. Equipments receive minor damages but they would be still operational.	No life damage. Equipments are damages, but the system still maintains its performance and critical conditions do not occur.
High	Without any damage and performance disturbance	No life damages. Equipments are damaged but they would maintain their performance.	No life damages. The equipments are damaged with possible temporary disturbance in system performance but the critical conditions do not occur.
Medium	No life damages. Equipments receive minor damages but they would maintain their performance.	No life damages. The equipments are damaged with possible disturbance in system performance	No life damages. The equipments are damaged with major disturbances in equipment and system performance however repairable and recoverable in an acceptable time
Low	No life damages. The equipments receive minor damages but the system maintains its performance	No life damages. The equipments are damaged with major disturbance in the equipment and system performance however repairable and recoverable in an acceptable time	Not necessary

Chapter 3

Seismic Evaluation Methods

3-Seismic Evaluation Methods

In this chapter the seismic evaluation methods of different power supply system's components and their application framework are presented based on seismic evaluation level. The details of these methods for each component comply with guidelines and codes related to their designing.

3-1-Target components

The target components in this guideline are introduced in table 3.1 through general grouping of line and stationary components. In regard to seismic performance evaluation, this grouping is performed as both the single performance of each component and system performance of multi-components comprising a system.

Table 3-1: Components categories

Type	Title	Performance	Components
Stationary	Power plant	Single components	Equipments
			Non-building structures
			Buildings
			Non-structural and subordinate components
		Systems	Different components
	Substation	Single components	Equipments
			Non-building structures
			Buildings
			Non-structural and subordinate components
		Systems	Different components
Line (Network)	Transmission	Systems	Different components
		Single component	Component itself
	Distribution	Single components	Equipments
			Non-building structures
			Buildings
			Non-structural and subordinate components
		system	Different components

3-2-Seismic evaluation methods of components

The primary and details seismic evaluation methods for stationary structures, including buildings, non-building structures, equipments, and non-structural and structural line and network components for different evaluation levels are as shown in table (3-2). In addition to the suggested cases in this table, also the laboratory methods could be used especially for non-structural equipments and components.

Table 3-2: seismic evaluation methods of components in different evaluation levels

Component's name	Level-1 evaluation methods	Level-2 evaluation methods	Level-2 evaluation methods
Building structures	Fast evaluation instructions	Fast evaluation instructions	Detailed evaluation using seismic rehabilitation instructions
Non-building structures	Evaluation using qualitative evaluation worksheets or using scoring methods	Controlling seismic behavior by reviewing primary design documents and using simple and static-equivalent (pseudo-static) methods of code	Software and numerical modeling and pseudo-dynamic, dynamic, and interactive behavior analysis
Outdoor equipments	Evaluation using qualitative evaluation worksheets or using scoring methods	Controlling general seismic stability by reviewing design documents and using: - Code's simple and static-equivalent methods - Empirical methods based on damage curves - Vulnerability spectrum method - using empirical screening	Software and numerical modeling and pseudo-dynamic, dynamic, and interactive behavior analysis
Non-structural components and indoor equipments	Evaluation using qualitative evaluation worksheets	Qualitative evaluation worksheets	Controlling general stability using static-equivalent methods or empirical methods
Aerial and underground transmission and distribution lines	Evaluation with qualitative evaluation worksheets or using scoring methods	Controlling seismic general stability under geotechnical hazards (slippage, faulting, liquefaction, etc.) and interactive effect of neighboring structures by reviewing design documents and using simple and empirical methods	Dynamic behavior analysis under geotechnical hazards (slippage, faulting, liquefaction, etc.) and interactive effect of neighboring structures and analytic and numerical modeling

Note: The general method for extracting damage functions and curves is presented in Appendix 2.

3-2-1-Buildings seismic evaluation

In addition to the issues addressed in determining the evaluation parameters, the key factors in evaluating the buildings' performance are as follows:

- Structure's economic value and years left from its operation life.
- Building's application including number of people inside the building exposed to danger and structural damage factors which would lead to releasing of dangerous materials and casualties outside the building.

- Structure's performance and economic and social effects in case of damages to its servicing in result of earthquake.
- Historical significance of the structure and effects of seismic rehabilitation on cultural and heritage sources.
- Site-specific seismic hazard.
- Relative costs of rehabilitation compared to its revenue.

The primary seismic evaluation in levels 1 and 2 of concrete and steel and monumental buildings is performed based on the President's Deputy of Strategic Planning and Control's instructions #364, namely Visual Fast Evaluation Method for Steel and Reinforced concrete Buildings.

The primary seismic evaluation in levels 1 and 2 of monumental buildings is performed based on the fast qualitative evaluation method presented in the President's Deputy of Strategic Planning and Control's instructions #364 for building with monumental materials.

The level-3 detailed evaluation of concrete and steel buildings is performed using the service descriptions presented in issue #251, titled Descriptions of Evaluation and Rehabilitation Services of Buildings and issue #360 of President's Deputy of Strategic Planning and Control, Buildings' Seismic Rehabilitation Instructions.

The detailed evaluation of current monumental buildings is performed using Seismic Vulnerability and Rehabilitation Instructions for Current Monumental Unarmed Buildings (Buildings Deputy of Ministry of Housing and Urban Development).

3-2-2-Non-building structures seismic evaluation

The primary seismic evaluation of non-building structures in levels 1 and 2, which is performed as component, could be carried out using the following methods:

- Reviewing the structure's primary seismic design documents considering the status like construction and current conditions, if the documents are available
- Inspection by preparing and using seismic worksheets considering the type of each structure and evaluation using qualitative scoring method
- Using models and simple and static-equivalent methods and seismic general stability control

Usually, in the primary seismic evaluation of non-building structures, the system inspection would not be performed. If the components are vulnerable in this stage, then the detailed evaluation is performed using both component and system approaches.

The level 3 detailed evaluation of non-building structures using numerical modeling and analysis. This inspection includes studying the dynamic and interactive behavior of the structure. Using the detailed method for complex structures or with unknown dynamic behavior or with considerable interaction with environment or other structures is mandatory.

3-2-3-Equipments seismic evaluation

The primary seismic evaluation in levels 1 and 2 is performed using the following approaches:

- Reviewing the seismic control documents considering the equipment state which include seismic laboratory documents and seismic performance control certificate of equipment's internal parts by manufacturers.

- Using quantitative scoring methods by issues #521 and #213 (Instructions for Seismic Evaluation of power plants and power substations facilities)
- Seismic empirical evaluation method using screening according to issues #512 and #513
- Seismic empirical evaluation method using seismic vulnerability spectrum according to issues #512 and #513
- Using simple and static-equivalent methods of code and seismic general stability control

Usually, the system inspection is not performed in equipment's primary evaluation. If the components are vulnerable in this stage, then the detailed evaluation would be performed using both components and system approaches.

The level-3 detailed evaluation of equipments is carried out using numerical modeling and analysis. This inspection includes studying the equipment's dynamic and interactive behaviors. Using the detailed method for complex structures or with unknown dynamic behavior or with considerable interaction with environment or other structures is mandatory.

3-2-4-Non-structural components seismic evaluation

The seismic evaluation of architectural components and indoor equipments like walls, shelves, false floors, and indoor facilities like piping, canals, wires, and cables are single-stage and is performed based on the following regulations and guidelines:

- Appendices power vital arteries design guides
- Building seismic rehabilitation instructions, issue #360
- Appendices of issues #512 and # 513 (Instructions for Seismic Evaluation of power plants and power substations facilities)
- Other valid and introduced references in this guideline
- Performing experiments and inspecting seismic performance of sample components

3-2-5-Network and lines seismic evaluation

The seismic evaluation of lines and network is carried out in two stages, component-stage for determining the vulnerability of each network's component, and system-stage for determining the vulnerability of the entire line or network range.

The primary evaluation of lines and network components in leve-1 performed through following methods:

- Reviewing network's seismic design documents, if available
- Preparing and using seismic worksheets according to the type of network components and using qualitative scoring method
- Using simple and static-equivalent method of code and seismic general stability control of line and network components
- Using current vulnerability curves of components

Lines and network system primary evaluation in level-1 could be performed using vulnerability combination formulation based on the reliability method.

The level-3 component detailed evaluation of lines and network could be carried out by the analytical method using calculation and numerical model.

The level-3 component detailed evaluation of lines and network could be performed using vulnerability combination formulation based on the reliability method.

The combination formulation could be performed based on the reliability method using guides from appendices of issues #512 and #513.

3-3-Inspection in Qualitative Evaluation

The inspection and completion of components' qualitative evaluation forms is one of the main stages of seismic evaluation in levels 1 and 2. The result of this activity, which leads to preparation of vulnerable components primary list and their vulnerability qualitative level, has a large effect on type and volume of studies. The local inspection and concluding their results should be performed by a qualified and legitimate engineer or a group of engineers.

Usually, the general steps of this activity are as follows:

- Holding sessions with employers, technicians, standard supervisors, safety engineers, and other stakeholders to discuss the inspection's goals and provide the inspection group with the necessary possibilities
- Identification and preparing the list of considered equipments, structures, and other components
- Categorization of vulnerability modes of considered components
- Preparing and completion of inspection worksheets
- Settling required coordination with process and operation safety team
- Collecting local data such as seismic hazard, faults location, current holes in soil and other geotechnical related issues.
- Local inspection of components and filling up the worksheets and documentation of obtained observations and information
- Reviewing maps, in necessary, in order to control the sufficiency of reinforced concrete structures, determining bracing details and/or determining items which are undetectable by visual inspection due to limitations such as fireproof coverings, isolations, and so forth.
- Listing weak and suspicious components for employers and/or standard supervisors including sufficient explanations
- Identification of consequences caused by components damage

During a destructive earthquake, there is the possibility of damaging outdoor facilities and their long-term destruction. In such cases, preparing items, such as support power generator equipments and water reserves, sounds reasonable in seismic evaluation and rehabilitation. The local inspection team should highlight the existence of other emergency systems effective on system performance in order to minimize earthquake effects. Especially, the necessity of fire alert and extinguish system, communication and preventive systems for non-stop performance after earthquake, should be emphasized.

The general technical considerations in an inspection are:

- Ground's seismic hazard level: in regions with low seismic hazard, the structures might be designed considering non-seismic lateral loads, such as wind, and are also resistant against earthquake but nonetheless the destructive displacements might also occur in seismic low levels.

- Secondary hazards intensity (faulting, soil displacement, and landslip): the inspection team should pay special attention to faults near site. Locations with the possibility of displacement and damage to buried lines and equipments relying on structural systems should be considered. When faults pass through site, the evaluation of the inspection team must be completed by performing additional geotechnical studies or other studies.
- Codes applied during construction: the applied codes and design methods might undergo major changes relative to the time of designing.
- For the evaluation of older facilities, more attention must be paid to current damages caused by structural age such as steel dent, damaged concrete, corrosion, etc.
- If the general quality of maintenance is not suitable, the local inspection team must consider and inspect details, such as number of lost bolts, unrepaired damages, changes and field modification, etc., through the structure's load transmission course as well as in connections.
- The process safety engineers and employers must be informed and assured of the safety primary inspection, pollution, or economic consequences and environmental impacts, through local inspectors.
- The local inspection team must always be aware of places susceptible to corrosion. These areas are especially associated to places with corrosive materials like acids and also amassed water places. Other cases in which the corrosion might become a problem are where the concrete covering is detached and rebar is exposed to environmental conditions.
- During inspection, the engineers could inspect installed facilities which have problems. These problems might be observed in welds, or installation of expansion anchor-bolts. For example, if the length of expansion anchors is not sufficient, they might not be as resistant as their design tensile capacity allows them.
- A piece from system, structure, storage cabinets, furniture, and storage equipments might move during earthquake. Due to this movement and consequently hitting a system or component, damages might be inflicted to that component or system which is called seismic interaction. Local inspections about possible interactions are one of the best items of component performance verification. Often, when there is not enough distance between two components, these interactions occur. Also, it might be due to slippage of non-braced facilities, movement of hanging pipes and/or cable trays, deflection of electric board and collision with adjacent boards, walls or structural member. Another example includes the hazard related to passageways with sharp supports. Another case of interaction could be the structural failure and overturn when different components fall due to anchor's lack sufficiency and hit other tools.
- For inspectors, the local asymmetric displacement is more important in case of facilities attached to different structural systems. Engineers must be aware of facilities' possible displacement states. These states include items such as connection pipes, ducts, canals, tubes, etc. In such cases, facilities must have enough flexibility against movement. Flexibility is a key characteristic to resist against vulnerability. It would be of special significance when using different foundations for equipments, when they are non-braced.
- One of the notable issues is the automatic fire alert and extinguishing system. The performance of water-sensitive electric equipments might be disturbed when placed under the sprinkler heads.

- Inspecting the current buildings' vulnerability adjacent to distribution network components and risk of their collision with network components, in case of destruction, must be evaluated. Therefore, first those building close enough to distribution network components must be highlighted which might collide network components in case of complete or partial destruction. After signifying the risky building adjacent to networks, the mentioned buildings must be evaluated against earthquake during the next step. The evaluation of building adjacent to distribution network for each case must be carried out according to the respective instructions (instructions #360 and # 364 of President's Deputy of Strategic Planning and Control, for buildings with reinforced concrete or steel structures, and instruction #376 for building with monumental materials) and using quantitative methods, as far as possible. The desired performance level in evaluation of such buildings, for the design's hazard level according to these instructions, should be considered equal to collapsing threshold and for components with high importance, equal to life safety. If it is impossible to perform quantitative evaluation for the expected building, it is mandatory to carry out complementary qualitative evaluations based on the mentioned instructions.

3-4-Collecting Required Information in Detailed Evaluation

Collecting required information of quantitative evaluation should be performed through a planned process. The current references for determining and collecting required information include:

1) Documents available during different designing, operation, and periodic maintenance stages: the available documents must be visually compared with the current condition of the network and updated, if necessary.
2) Vesting and collecting information using visual methods and required measurements: in doing so, boring and destruction of coverings and upper layers should be performed (without imposing any weakness or disturbance to components' performance or behavior) and the required characteristics and parameters should be determined.
3) Performing required tests: if necessary and lack of required information based on current documents or catalogues, the information must be prepared and collected using experimental methods. The main application of test methods is for determining required properties of soil, site, and materials' mechanical properties. Totally, the nondestructive tests are preferred. If it is necessary to perform tests on connecting tools such as bolts, it would be better to be replaced with their identical item. Anyway, during boring or testing, inflicting damages or weaknesses to each current component of the network should be avoided.

3-4-1-Collecting documents of design and operation

At the beginning of seismic evaluation studies, the structural documents of facilities, such as buildings, non-building structures, and equipments, should be collected and reviewed as far as possible. Also, the executive maps should be matched with what has been implemented and be updated if not consistent. Also, it is necessary to collect information on changes, possible repairs, and influential events on facilities' behavior.

Materials and soil test information as well as hazard analysis studies should be collected and reviewed as far as possible.

3-4-2-Visual inspection and extracting visible and effective problems

In this stage of data collection, study and reviews are performed to record the visible and effective problems which create a specific and obvious weakness in facilities' seismic behavior. Comparing executive maps, like construction and installation, with the available facilities is mandatory in this stage.

3-4-3-Performing materials and soil tests and hazard analysis studies

Based on the assessment of the consulting engineering, if there was not sufficient documents and information for primary or detailed evaluations from the previous reviews, this stage of data collection must be performed following the employer's approval.

Conditions which require materials and soil tests and tests' levels are presented in table (3.3). The definition of standard and comprehensive tests for buildings is in accordance with the Buildings Seismic Rehabilitation Instruction (issue #360). In this guideline, no specific definition is presented for non-building structures and equipments for tests, and the required tests' level in these cases should be determined by the consulting engineer's assessment and employer's approval.

Table 3-3: Required tests of materials and soil

System's Relative Importance	Materials and Soil Information	Required Test Level for Materials and Soil
Very high	Available	Standard
	Not Available	Comprehensive
High	Available	-
	Not Available	Standard
Medium	Available	-
	Not Available	Standard
Low	Available	-
	Not Available	-

3-5-Seismic Evaluation Using Structure's Modeling and Numerical Analysis

The modeling and numerical analysis methods of structures are based on determining and comparing seismic demand-capacity of equipments, structures, and their joints. Modeling and numerical analysis methods of structures include the following two major aspects.

- Preparing a proper model according to the equipment's mechanical and dynamic properties
- Prepared seismic loading and numerical analysis of structure's model

For equipments, the applied damping and mass in modeling and numerical analysis of equipment structures are considered equal to contents of manufacturers' catalogues, test sheets, and/or based on results from analytic methods. In case information is missing, the 2% damping is suggested. Table (3.4) provides amount of mass and damping for some equipments.

Table 3-4: Mechanical and dynamic properties of equipments

Type of equipment	Maximum mass or typical density	Damping
Control boards and panels	600 kg/m3	5
Transformers	7 tons	5
Horizontal pumps	7 tons	5
Vertical pumps	2 tons	3
Air compressors	4 tons	5
Motor – generator and motor – combustion generator	-	5
Batteries and their support shelves	-	5
Battery chargers and invertors	700 kg/m3	5
Equipments shelves	300 kg/m2 (from vertical section)	3
General equipment cabinets	3 times of cabinet container’s weight	5

The numerical analysis methods of structures suggested by this guideline are as follows:

- Equivalent static method
- Spectrum method
- Time-history method

3-5-1-Equivalent static method

The equivalent static method for building structures and non-building structures is similar to the presented methods for their design stage. In seismic analysis of equipments in which the vibration first mode is accepted as the dominant mode, the equivalent static method is suggested similar to the section of non-building structures regulations of Standard 2800.

For equipments with natural period smaller than 0.03s, applying the force, obtained from multiplying acceleration by different parts’ mass, to their center of mass, without any resonance factor, is acceptable.

3-5-2-Spectrum method

For more complex equipments with numerous vibration modes which are sufficiently far from each other, using the spectrum analysis in accordance with the regulations of non-building structures of standard 2800 is suggested.

3-5-3-Time-history method

For seismic evaluation of complex equipments with close vibration modes, using the time-history analysis in accordance with the regulations of non-building structures of standard 2800 is suggested.

3-6-Considering the Systems Seismic Interaction Effect

The systems seismic interaction is a set of effects on seismic behavior and intensifying consequences of earthquake. Undesired changes in dynamic properties from adjacent systems structural interaction, collision, falling, and relative displacement of adjacent systems and changes in environmental and operational conditions which lead to disturbance in systems' or personnel's performance, are some of the cases which cause seismic interaction.

The regular reasons of interaction in power plants are categorized as follows:

1- Adjacency: any effect which leads to malfunctioning caused by systems adjacency including: collision, relative deformation, and structural interaction
2- Failure and fall down: any effect which leads to malfunctioning caused by damage, failure, and fall down
3- Sprinkler: effects of pipes failures or performance of fire extinguishing sprinklers which might lead to short circuit or inaccessibility to power plant components.
4- Inundation: effects caused by systems flooding and their inaccessibility
5- Fire: effects caused by fire like smoke spreading and systems destruction

Each of power plant systems which are in the verge of negative effects of above mentioned interactions is "target of interaction" and systems which their malfunctioning would lead to these interactions are "source of interaction". If the interaction causes damages or malfunctioning of the system, it would be called "considerable interaction" and if the negative effect is negligible, then it would be "inconsiderable interaction".

Considering the seismic interaction effects in evaluation of "target of interaction" systems could be performed using one of the following four approaches:

1-Neglecting the interaction effects (inconsiderable interaction)
2- Modification of "source of interaction" systems in order to eliminate the interaction effects (considerable interaction)
3- Elevating the relative importance of "source of interaction" systems to the limit of "target of interaction" systems (considerable interaction)
4- Using performance modification parameter for "target of interaction" equipments in the scoring method (considerable interaction) unless the "source of interaction" equipments are evaluated assuming the relative importance equal to the importance of "target of interaction" equipments (approach 3).

3-7-Acceptance Criteria

If the effects from imposed loads to electric devices consistent with the following loading combination are larger than the equipment's components seismic capacity, the equipment would be considered as vulnerable. It is noteworthy that, in case of electric devices, the potential of short circuit, which is a source for one of the considerable imposed loads, might be intensified during earthquake occurrence:

Operational load impact + short circuit load impact + dead weight load impact + earthquake impact

In regards to the type of available buildings in a distribution network, the acceptance criteria presented in the applied instructions should be used.

In regards to other components (non-building structures and equipments) in a distribution network, they would be whether accepted or not based on comparing seismic effects (resulted from their seismic analysis under loads combinations) with seismic capacity of each of them. In regards to aerial line posts, their displacement must also be examined, in addition to the seismic capacity, in order to prevent overturn.

3-7-1-Imposed loads combinations

Generally, the required loads combinations for seismic vulnerability evaluation of non-building components are as follows:

Dead loads + operational loads + horizontal seismic load (in two independent directions) + vertical seismic load (in two independent directions)

In the above combination, at hazard level, the loads caused by earthquake (horizontal and vertical) should be multiplied by a load factor of ¼.

3-7-2-Structural components' strength and capacity

The capacity and strength of different components based on type of materials is obtained as follows using the respective standards:

- The seismic capacity of parts made of ceramic and porcelain, such as insulators, is considered according to the respective standards and catalogues and/or equal to 85% of ultimate strength of their materials. The above mentioned capacity should be considered in every hazard level.
- The seismic capacity of steel components for hazard level-2 or design should be considered equal to 1/7 of allowable stresses (and/or ultimate strengths) and for hazard level-1 or operation should be equal to allowable stresses according to section 10 of National Building Code (NBC).
- The seismic capacity of reinforced concrete components for hazard level-2 should be considered equal to the nominal strength of components (with material's strength reduction factor) and for operational hazard level should be equal to the strength equivalent to the cracking limit according to section 9 of NBC.
- The seismic capacity of aerial lines wooden posts for design and operational hazard level are assessed based on their standard category, based on ultimate strengths (for design level) and cracking limit (for operational hazard level) related to each class.
- The seismic capacity of aerial lines wires for design hazard level should be considered equal to yield tensile strength and for operational hazard level should be equal to allowable tensile stress according to section 10 of NBC.
- The seismic capacity of ground line cables for design hazard level should be considered equal to the longitudinal strain equivalent to the cable's failure limit and for operational hazard level should be equal to longitudinal hazard level equivalent to the allowable tensile stress.

3-7-3-Controls related to displacement and overturn

In regards to non-braced parts and equipments as well as aerial lines, in addition to examining the seismic demands and capacity in terms of strength, it would be necessary to control overturn, slippage, and displacement, which are performed as follows:

- Non-braced equipments and pieced must be controlled against imposed seismic forces, in regards to overturn and slippage. The minimum values of required reliability for overturn and slippage in both hazard levels are 1.75 and 1.5, respectively.

- The escape value of aerial line posts (ratio of difference between displacements of both ends of post to its height or post's rotation angle) for design hazard level is limited to 0.02 and for operation hazard level to 0.01.

3-7-4-Equipments bracing strength and capacity

In braced equipments and parts in concrete or other materials, the capacity of bracings should be determined based on the third chapter of issue #512.

3-7-5-Acceptance criteria in nonlinear dynamic methods

Totally, in nonlinear dynamic methods, evaluation and acceptance of different components are performed using criteria composed of force and displacement combination. In power distribution networks, considering the expected performance of equipments and network components, the stresses and internal forces created in non-ductile components (controlled by force) should be controlled similar to linear methods (presented in previous paragraphs), in case of performing nonlinear analyses. In ductile components which enter the nonlinear range, created displacements and rotations should be to the extent that does not disturb the evaluated component's expected performance. Identifying these items should be performed based on equipments' technical properties and experts' judgment.

Chapter 4

Seismic Rehabilitation Procedure

4-1-Rehabilitation Prioritization

The rehabilitation prioritization is carried out based on the following indices:

- Layer index, I_L
- Changing expected performance level
- Rehabilitation cost
- Feasibility of rehabilitation method

The general method to determine the rehabilitation priority is based on risk analysis. In order to perform this analysis it is necessary to determine the consequences of not rehabilitating based on vulnerability studies' results and to decide on this basis. The consequences of not rehabilitating are verified in five categories, namely casualties, possibility of social and political crises according to time of power-cut, direct financial damages to facilities, economic damage caused by vital artery power-cut, environmental damages. In fact, these criteria determine the general safety of structure or equipment.

The highest rehabilitation priority is designated to the first two categories. In other cases, comparing the rehabilitation cost and predicted damage costs, the risk of not rehabilitating is determined and is decided on this basis. In risk analysis, different damage modes and also rehabilitation levels could be compared with each other.

4-2-Seismic Rehabilitation Procedure

The seismic rehabilitation of structures and equipments is a error and trial method and is performed following ensuring the vulnerability of the structure and based on the following steps:

1- Choosing the rehabilitation methods based on damage mode of equipments, structures, and their required performance

2- Applying changes caused by each rehabilitation method in structural model and reexamining vulnerability to obtain the expected suitable performance

3- Comparing acceptable rehabilitation methods based on cost, time, and executive feasibility as value engineering, prioritizing each structure's and equipment's rehabilitation methods

4- Seismic rehabilitation prioritization of system components based on paragraph 4.1

Chapter 5

Seismic Rehabilitation Methods

5-1-Rehabilitation Method Selection Approach

The structures and equipments seismic consequences reduction methods could be divided into two general groups:

- Hardware methods as structural rehabilitation and modification and finally renovation
- Software methods as changing operation schedule, changing expected performance level, and increasing safety and reducing secondary incidents occurrence possibility

The seismic rehabilitation method depends on the dominant damage mode of structures and equipments. Thus, selecting a proper rehabilitation method has direct relation with the vulnerability evaluation results validity. In these studies, the damage mode and damage amount should be signified. Indeed, depending on the hazard level, the damage mode could differ, which this should be considered during selecting the rehabilitation method so that it would be possible to control all possible damage modes by performing proportionate rehabilitation exercises.

In reviewing damage modes and presenting rehabilitation methods, all primary and secondary damage modes must be taken into account. The secondary damage modes include permanent ground deformations, fire, fire, explosion, structures collision, destruction rubble fall-down of other components on them, and other cases.

5-2-Rehabilitation Method Type

In this section, the general seismic rehabilitation methods of structures and electric equipments in four sections of power plant, super-distribution substations, super-distribution network, and urban distribution network are suggested based on the observed damage modes in past earthquakes.

5-2-1-Power plants

The components examined in power plants include non-building structures, equipments, and buildings which are discussed separately.

5-2-1-1-Non-building structures

The non-building structures of power plants have various and numerous damage modes. These structures could be divided into three general groups:

1- Special and shell structures like cooling towers, flues, vents, and tanks
2- Linear and connection structures like underground canals and underground ducts, busbar, racks, on-ground and under-ground pipes
3- Indoor and outdoor subordinate structures like cut-off walls, retaining walls, load bearing false floors, and lights and communication supports

Table (5-1) lists types of these structures while introducing their observed and possible seismic damage modes, the common reasons for occurrence of these damage modes, and damages general methods of their rehabilitation methods based on respective damage mode and reason.

Seismic damage modes of non-building structures of power plants are not limited to items provided in table (5-1) and the consultant must examine the occurrence possibility of other seismic damage mode based on local conditions and vulnerability studies results, for each case.

Table 5-1: Seismic rehabilitation guide of power plants' non-building structures

Component	Possible damage mode	Damage reason	Rehabilitation method
Wet cooling tower	Support structure damage and overturn	Deformations and ground high settlements Insufficient lateral rigidity of support structure Insufficient strength of anchor rods connecting structure to foundation	Underneath soil rehabilitation or structure's foundation strength Adding internal or external lateral bracing or reinforced structure's members Adding column late and injection or mechanical anchor rod
Dry cooling tower	No history		
Flue	Support structure damage and overturn	Deformations and ground high settlements Insufficient lateral rigidity of support structure Insufficient strength of anchor rods connecting structure to foundation	Underneath soil rehabilitation or structure's foundation strength Adding internal or external lateral bracing or reinforced structure's members Adding column late and injection or mechanical anchor rod
Vent	Bending failure	Insufficient buckling axial strength and shear strength	Confine with FRP Confine with metal jacket
Fuel cylindrical tank	Failure of pipe or connection valve or product's leakage from valve or inlet and outlet pipes Outwards elephant-foot buckling of tank's shell in lower part Floating ceiling structure's failure and its fall down with possible pontoon damage Creating spark and fire in connection of ceiling sheet and wall	High relative deformation between tank and pipe due to tank's lengthening or due to imposed movements of pipe and its valve Insufficient axial capacity of wall sheet and tank not anchored to foundation Fluid's uncontrolled turbulence inside tank and insufficient capacity of pontoons	Bracing tank in order to decrease displacement and lengthening or using flexible pipe's connection to tank with expansion joints Replacing wall sheet, external post-tensioning, adding ring hardener to wall sheet, anchoring to foundation Reinforcing pontoon, replacing pontoon, adding pontoon, reinforcing ceiling with hardener, replacing ceiling sheet Embedding cushion at ceiling and wall connection, replacing connection rubber
Underground canal	Wall failure and soil filling in Canal's wall cracking and opening of contraction gaps Ceiling caps falling into canal Injury of cables on handles	Insufficient strength capacity of wall's concrete for bearing soil's lateral pressure Ground high deformation and improper openings design Insufficient support area for caps on support Sharp edges of cable seat handle	Reinforcing canal's concrete wall from outside or with internal bracing Adding opening or longitudinal reinforcement to remove opening At least embedding 10 cm support area in each side or embedding brake Removing cable seat's handle sharpness by replacing or modifying the handle

Component	Possible damage mode	Damage reason	Rehabilitation method
On-ground piping	Detachment of pipes from equipments or leakage from pipe at its connection to equipments or local damage in this location Crumpling and buckling of pipe wall or pipe wall failure in pipe's length or its support Damage due to rubble fall down on pipe Connections cracking and failure and leakage from them	High relative deformation between pipe and equipment due to excessive displacement and oscillation of equipment or inflexibility of pipe Insufficient strength of wall or brittle pipe materials or improper connection type and support arrangement Equipment, materials, and rubble fall down on pipes Brittleness and insufficient strength of connections and pipe junctions or excessive movement of pipe supports	Equipment and pipe bracing, embedding flexibility at connection as pipe's topology changes or using expansion connection Replacing pipe, reinforcing wall with FRP, changing force distribution in pipe with replacing and modifying supports Eliminating material fall down threat, protecting wall using false covering, burying Using weld connections in steel pipes, embedding flexibility at connection as pipe's topology changes and providing additional bends while complying with product transmission inside pipes or using expansion connections, changing force distribution in pipe with replacing and modification of supports, reinforcing walls using FRP
Underground piping	Detachment of pipes from structures or leakage from pipe's connection to building or local damages in this location Crumpling and buckling of pipe's shell or its failure in the direction of pipe's length Cracking and failure of connection and leakage from them	High relative deformation between pipe and structure due to structure's excessive displacement or constrained pipe's connection to structure Insufficient strength of shell and brittleness of pipe's materials or improper connection type and ground intense movements Brittleness and insufficient strength of connections and bends and pipes' junctions	Embedding freedom and sufficient flexibility at pipe's connection to structure using pipe sleeve or using expansion connection Replacing pipe, reinforcing shell with FRP, changing force distribution in pipe or make soil surrounding the pipe flexible Using weld connection in steel pipes, embedding flexibility at connection as pipe's topology changes and creating additional bends while complying with product transmission considerations inside pipes or using expansion joints, reinforcing connection's shell with FRP, using pipe sleeve, make soil surrounding the pipe and connection flexible
False floor	Failure of support legs or their bracing to floor	Lacking of insufficient lateral strength, weakness of legs' bracing to floor, placing heavy equipments on floor and lacking of separate reinforced seat	Embedding bracing in legs, reinforcing legs' bracing to floor, placing heavy equipments on separate reinforced seats
Walls	Superficial or deep diagonal shear cracking in body and around openers	Insufficient shear capacity, not being reinforced, uncontrolled connection to frame,	External reinforcement of wall for bearing lateral load, embedding internal or external cradling with metal straps or FRP or FRP sheets or shotcrete with reinforcement 3D

Component	Possible damage mode	Damage reason	Rehabilitation method
	Vertical crack at connection to column Overturn	lacking of sufficient and proper cradling Uncontrolled connection to frame, lacking of sufficient and proper cradling Improper and unreinforced connection to frame, lacking of sufficient and proper cradling	mesh or panel or reinforcing injection and mechanical bracing rods, modifying connection to frame Modifying connection to frame, embedding internal or external cradling Reinforcing connection to frame, embedding internal or external cradling

5-2-1-2Equipments

Equipments of power plants could be reviewed in three following groups:

1- Main power generation equipments and related support equipments, such as boiler, generator, transducer, pump, valve, compressor

2- Equipments of conversion and switch substations, such as transformers and other substation equipments which are discussed in substations section.

3- Controlling and support indoor equipments, such as control panels, battery shelves, busbar, condenser, fan, air conditioner and chiller, lighting system and fire extinguisher, computer equipments and monitor, shelves, communication equipments

Table (5-2) shows the list of these equipments presenting observed and possible seismic damage modes, common occurrence reasons of these damage modes and their rehabilitation general method based in damage mode and reason. Seismic damage modes of power plant equipments are not limited to items provided in table (5-2) and the consultant must examine the occurrence possibility of other seismic damage mode based on local conditions and vulnerability studies results, for each case.

Table 5-2: Seismic rehabilitation guide for power plant equipments

Component	Possible damage mode	Damage reason	Rehabilitation method
Transformer	Overturn and slippage Failure or oil leakage from insulator Radiator detachment Oil tank detachment	Uncontrolled slippage due to lack of proper lateral bracing or being placed on wheels or rail Uncontrolled vibrations of insulator Lack of lateral bracing system Lack of lateral bracing system	Replacing wheel with anchored seat Attaching with anchor rod to foundation Lateral metallic support attached to foundation Replacing ceramic insulator with composite Reinforcing cap's connection against leakage Embedding proper lateral bracing in support Embedding proper lateral bracing in transformer's body Embedding proper lateral bracing in support Embedding proper lateral bracing in transformer's body
Boiler	Slippage caused by failure in support leg's connection Damages of anchor rods inside foundation	Weakness in connection or welding and bolt Insufficient amount of anchor rod or foundation concrete and bracing rod weakness	Reinforcing boiler's body connection to supports steel leg Increasing the number of bracing rods and controlling slippage and overturn modes
Heat exchanger	Damaged pipe's connection to boiler's body Slippage in result of weakness in leg's connection	Uncontrolled displacement and vibration Weakness in connection or weld and bolt	Increasing the number of bracing rods and controlling displacement using flexible connection Reinforcing structure's body attachment to support's steel leg
Pump and valve	Damaged pipe connection	Uncontrolled displacement and vibration	Attaching using anchor rod to foundation Using pipe's flexible connection Embedding seismic separator in leg
Compressor	Damaged pipe connection	Uncontrolled displacement and vibration	Attaching using anchor rod to foundation Embedding seismic separator in leg
Battery shelf	Overturn	Lack of lateral bracing system	Embedding a lateral bracing for shelves containing batteries
Control or distribution panel	Overturn	Lack of lateral bracing system	Attaching with bracing rod to floor Lateral connection to wall Attaching to ceiling Attaching panels to each other

Component	Possible damage mode	Damage reason	Rehabilitation method
Busbar	Detachment and failure of connections	Uncontrolled relative displacement	Replacing tube aluminum busbar with wire while embedding sufficient play and freedom Using mechanical parts which could get opened and closed in busbars' connections
Condenser, fan, air conditioner, and chiller	Overturn	Lack of lateral bracing system	Attaching with anchor rod to floor Lateral connection to wall Embedding seismic separator in leg
Lighting system	Wire and power cut	Uncontrolled relative displacement	Embedding sufficient play and freedom for wire or cable
Fire extinguish system	Overturn	Lack of lateral bracing system	Attaching with anchor rod to floor Lateral connection to wall
Computer equipments and monitor	Overturn	Lack of lateral bracing system	Attaching with bolt or glue to a braced table Attaching to each other Attaching with bolt to wall
Shelves	Overturn	Lack of lateral bracing system	Attaching with anchor rod to floor Lateral connection to wall Attaching to ceiling Attaching shelves to each other
Communication equipments	Overturn	Lack of lateral bracing system	Attaching with bolt or glue to a braced table Attaching to each other Attaching with bolt to wall

5-2-1-3-Buildings

The seismic rehabilitation of buildings is carried out based on seismic rehabilitation instruction (issue #360, President's Deputy of Strategic Planning and Control).

5-2-2-Substations

The examined components in substations include non-building structures, equipments, and buildings which are discussed separately.

5-2-2-1-Non-building structures

The non-building structures of substations have different and numerous damage modes. These structures could be divided into three general sections:

(1) Truss or frame special structures like gantries

(2) Line and communication structures, such as underground canals and ducts, busbars, and equipments' connection wires

(3) Indoor and outdoor subordinate structures, such as cut-off walls, retaining walls, load bearing false floors, and light posts

Table (5-3) shows the list of these equipments presenting observed and possible seismic damage modes, common occurrence reasons of these damage modes and their rehabilitation general method based in damage mode and reason. Seismic damage modes of power plant equipments are not limited to items provided in table (5-3) and the consultant must examine the occurrence possibility of other seismic damage mode based on local conditions and vulnerability studies results, for each case.

Table 5-3: Seismic rehabilitation guide for substations' non-building structures

Component	Possible damage mode	Damage reason	Rehabilitation method
Underground canal	→ Wall failure and soil filling in → Canal's wall cracking and opening of contraction gaps → Ceiling caps falling into canal → Injury of cables on handles	→ Insufficient strength capacity of wall's concrete for bearing soil's lateral pressure → Ground high deformation and improper openings design → Insufficient support area for caps on support → Sharp edges of cable seat handle	→ Reinforcing canal's concrete wall from outside or with internal bracing → Adding opening or longitudinal reinforcement to remove opening → At least embedding 10 cm support area in each side or embedding brake → Removing cable seat's handle sharpness by replacing or modifying the handle
Cables	→ Cables detachment from structure or cut at connection to the building or canal or other equipments → Failure of joint and cable connections	→ High relative deformation between cable and structure due to excessive displacement or constrained cable connection to structure → Brittleness and insufficient strength of joints	→ Embedding freedom and flexibility at cable connection point to structure using non-sharp proper pipe sleeve, predicting a little excessive length in cable → Replacing, modifying, or removing joint, changing force distribution in cables by making the surrounding soil flexible, using pipe sleeve
False floor	→ Failure of support legs or their bracing to the floor	→ Lack of sufficient strength, weakness in legs' bracing to the floor, placing heavy	→ Embedding bracing in legs, reinforcing legs' bracing to the floor, placing heavy equipments on separate reinforced seat

Component	Possible damage mode	Damage reason	Rehabilitation method
		equipments on floor and lack of separate reinforced seat	
Walls	→ Superficial or deep diagonal shear cracking in body and around openers → Vertical crack at connection point to column → Overturn	→ Insufficient shear capacity, being unreinforced, uncontrolled connection to frame, lack of sufficient and proper cradling → Uncontrolled connection to frame, lack of sufficient and proper cradling → Improper and unreinforced connection to frame, lack of sufficient and proper cradling	→ External reinforcement of wall for bearing lateral load, embedding internal or external cradling with metal straps or FRP or FRP sheets or shotcrete with reinforcement 3D mesh or panel or reinforcing injection and mechanical bracing rods, modifying connection to frame → Modifying connection to frame, embedding internal or external cradling → Reinforcing connection to frame, embedding internal or external cradling

5-2-2-2-Equipments

Substations equipments could be discussed in two following groups:

1- Main conversion and switching equipments, such as conversion transformer, lightning rod, cut-off switch, circuit breaker, current transformer, capacitor

2- Indoor control and support equipments, such as control panels, battery shelf, busbar, condenser, fan, air conditioner and chiller, lighting and fire extinguish systems, computer equipments and monitor, shelves, and communication equipments

Table (5-4) shows the list of these equipments presenting observed and possible seismic damage modes, common occurrence reasons of these damage modes and their rehabilitation general method based in damage mode and reason. Seismic damage modes of power plant equipments are not limited to items provided in table (5-4) and the consultant must examine the occurrence possibility of other seismic damage mode based on local conditions and vulnerability studies results, for each case.

Equipments of GIS gas substations have less vulnerability history and are not presented in table (5-4). Samples of rehabilitation details and seismic performance control of equipments are presented in figures (5-1)-(5-12).

Table 5-4: Seismic rehabilitation guide of substations equipments

Component	Possible damage mode	Damage reason	Rehabilitation method
Transformer	Overturn and slippage Failure or oil leakage from insulator Radiator detachment Oil tank detachment	Uncontrolled slippage due to lack of proper lateral bracing or being placed on wheels or rail Uncontrolled vibrations of insulator Lack of lateral bracing system Lack of lateral bracing system	Replacing wheel with anchored seat Attaching with anchor rod to foundation Lateral metallic support attached to foundation Replacing ceramic insulator with composite Reinforcing cap's connection against leakage Embedding proper lateral bracing in support Embedding proper lateral bracing in transformer's body Embedding proper lateral bracing in support Embedding proper lateral bracing in transformer's body
Current transformer (top core and down core)	Overturn, bending, local failure, and cracking mostly in top core current transformers	High mass concentration in height in top core transformers and brittleness of equipments' materials	Replacing with composite or resistant types Seismic separation of support structure from foundation Seismic separation and flexibility of ceramic connection cap to leg Energy depreciation in support structure using dampers Providing sufficient play in connection conductors to decrease adjacent equipments' interaction effects
Reactor	Overturn and slippage Failure or oil leakage from insulator Reactor detachment Oil tank detachment	Uncontrolled slippage due to lack of proper lateral bracing or being placed on wheels or rail Uncontrolled vibrations of insulator Lack of lateral bracing system Lack of lateral bracing system	Replacing wheel with anchored seat Attaching with anchor rod to foundation Lateral metallic support attached to foundation Replacing ceramic insulator with composite Reinforcing cap's connection against leakage Embedding proper lateral bracing in support Embedding proper lateral bracing in transformer's body Embedding proper lateral

Component	Possible damage mode	Damage reason	Rehabilitation method
			bracing in support Embedding proper lateral bracing in transformer's body
Voltage transformer (with or without wave trap)	Overturn, bending, local failure, and cracking	High mass concentration in height and brittleness of equipments' materials	Replacing with composite or resistant types Seismic separation of support structure from foundation Seismic separation and flexibility of ceramic connection cap to leg Energy depreciation in support structure using dampers Providing sufficient play in connection conductors to decrease adjacent equipments' interaction effects
Station transformer	Overturn and slippage Failure or oil leakage from insulator Radiator detachment Oil tank detachment	Uncontrolled slippage due to lack of proper lateral bracing or being placed on wheels or rail Uncontrolled vibrations of insulator Lack of lateral bracing system Lack of lateral bracing system	Replacing wheel with anchored seat Attaching with anchor rod to foundation Lateral metallic support attached to foundation Embedding proper lateral bracing in support Embedding proper lateral bracing in transformer's body Embedding proper lateral bracing in support Embedding proper lateral bracing in transformer's body
Circuit breaker	Bending and cracking	Brittleness of equipment materials Adjacent equipments interaction with tension of wire attached to equipment	Replacing with composite or resistant type Seismic separation of support structure from foundation Seismic separation and flexibility of ceramic connection cap to leg Energy depreciation in support structure using dampers Providing sufficient play in connection conductors to decrease adjacent equipments' interaction effects
V, T, and I shaped cut-off switch	Overturn, bending, local failure, and cracking often in V and T types	High mass concentration in height and brittleness of equipment materials Adjacent equipments	Replacing with composite or resistant type Seismic separation of support structure from foundation

Component	Possible damage mode	Damage reason	Rehabilitation method
		interaction with tension of wire attached to equipment	Seismic separation and flexibility of ceramic connection cap to leg Energy depreciation in support structure using dampers Providing sufficient play in connection conductors to decrease adjacent equipments' interaction effects
Lightning rod	Overturn, bending, local failure, and cracking	High mass concentration in height and brittleness of equipment materials Adjacent equipments interaction with tension of wire attached to equipment	Replacing with composite or resistant type Seismic separation of support structure from foundation Seismic separation and flexibility of ceramic connection cap to leg Energy depreciation in support structure using dampers Providing sufficient play in connection conductors to decrease adjacent equipments' interaction effects
Capacitor	Overturn	Lack of lateral system	Embedding lateral bracing for shelves containing capacitors' bank
Battery shelf	Overturn	Lack of lateral bracing system	Embedding a lateral bracing for shelves containing batteries
Control or distribution panel	Overturn	Lack of lateral bracing system	Attaching with bracing rod to floor Lateral connection to wall Attaching to ceiling Attaching panels to each other
Busbar	Detachment and failure of connections	Uncontrolled relative displacement	Replacing tube aluminum busbar with wire while embedding sufficient play and freedom Using mechanical parts which could get opened and closed in busbars' connections
Condenser, fan, air conditioner, and chiller	Overturn	Lack of lateral bracing system	Attaching with anchor rod to floor Lateral connection to wall Embedding seismic separator in leg
Lighting system	Wire and power cut	Uncontrolled relative displacement	Embedding sufficient play and freedom for wire or cable

Component	Possible damage mode	Damage reason	Rehabilitation method
Fire extinguish system	Overturn	Lack of lateral bracing system	Attaching with anchor rod to floor Lateral connection to wall
Computer equipments and monitor	Overturn	Lack of lateral bracing system	Attaching with bolt or glue to a braced table Attaching to each other Attaching with bolt to wall
Shelves	Overturn	Lack of lateral bracing system	Attaching with anchor rod to floor Lateral connection to wall Attaching to ceiling Attaching shelves to each other
Communication equipments	Overturn	Lack of lateral bracing system	Attaching with bolt or glue to a braced table Attaching to each other Attaching with bolt to wall

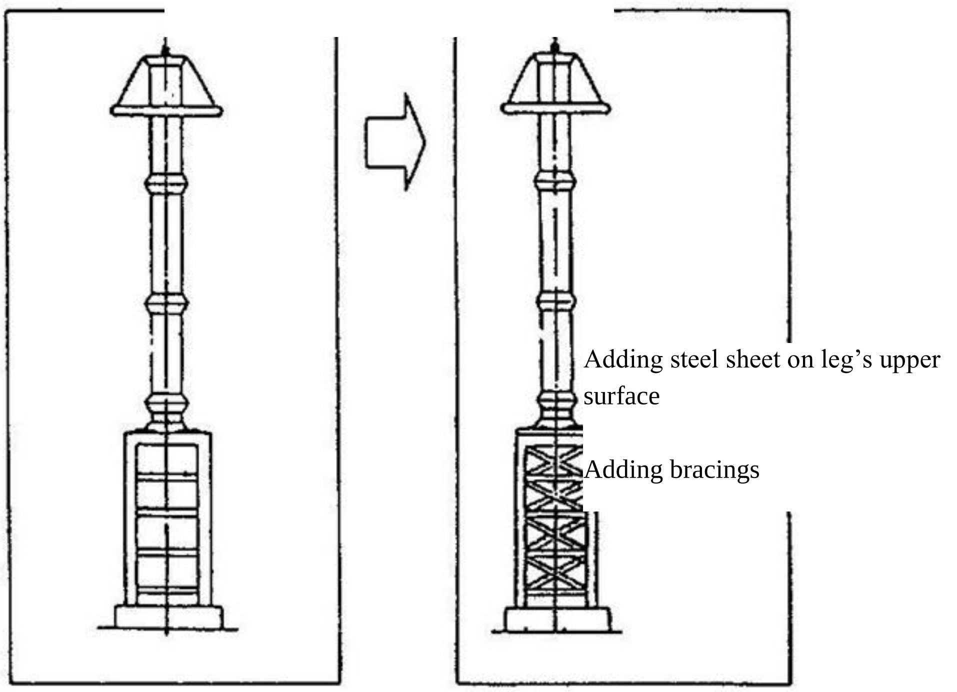


Figure 5-1: Equipments rehabilitation using support reinforcement and replacing fragile insulators with resistant composite insulator

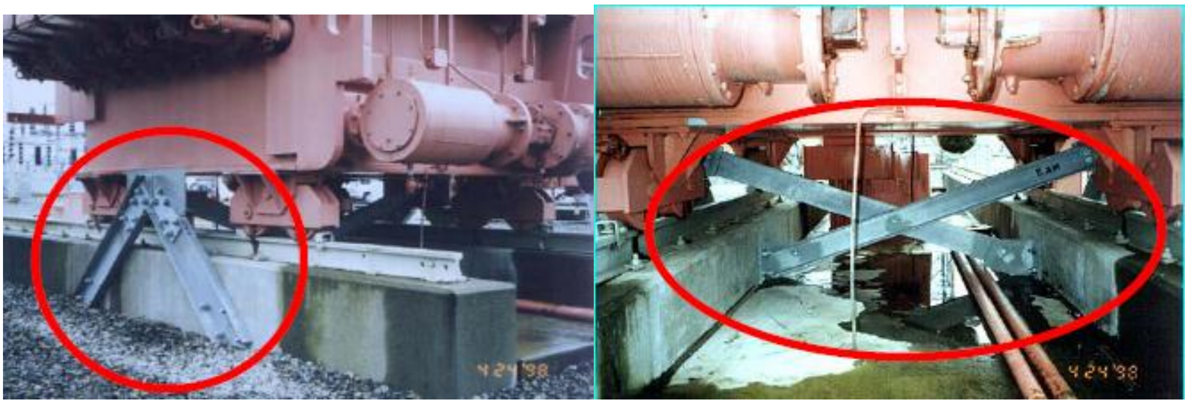


Figure 5-2: Stabilizing transformers body against overturn and slippage with bracings in leg

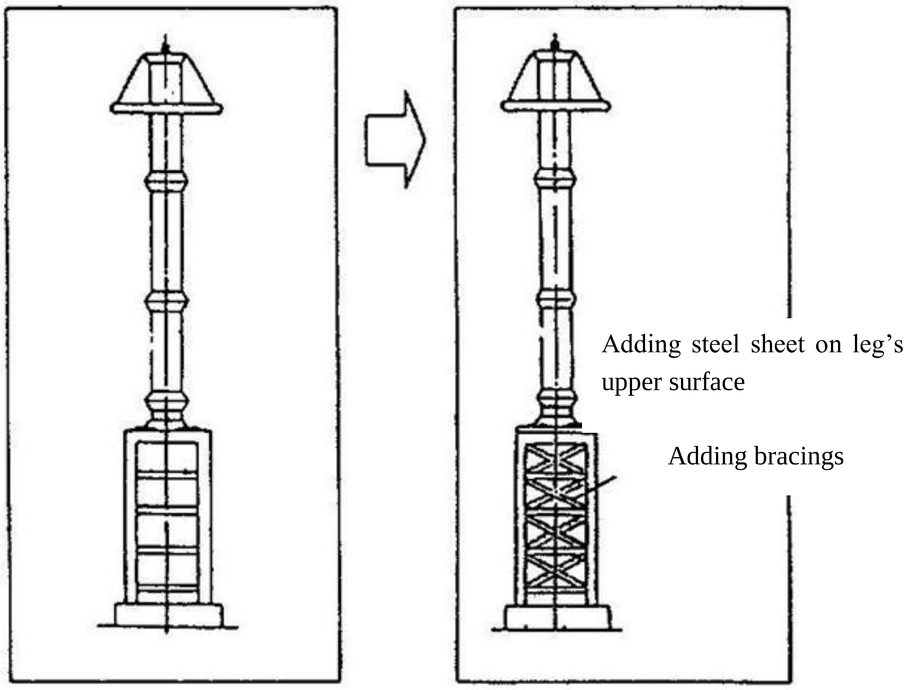


Figure 5-3: Equipment rehabilitation by increasing rigidity and changing vibration properties

Figure 5-4: Embedding brake in transformer's leg for controlling slippage mode

Figure 5-5: Reinforcing bracing of transformer's radiator

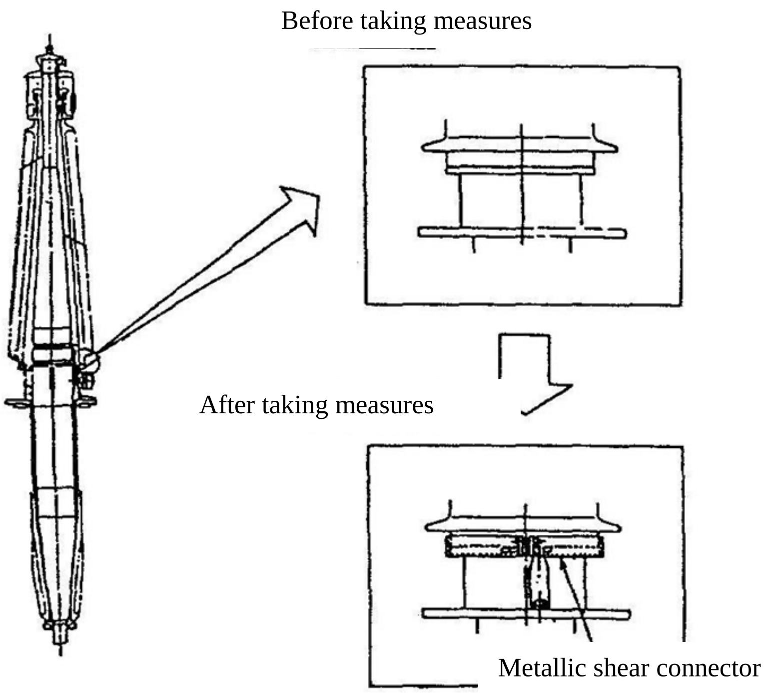


Figure 5-6: Insulator connection rehabilitation for controlling connection's failure and oil leakage modes

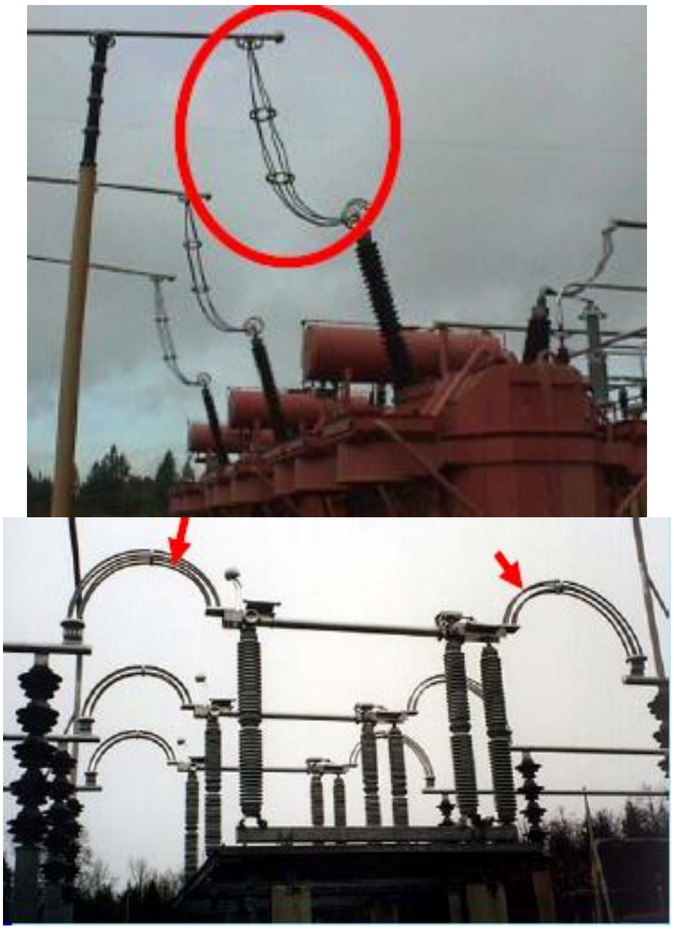


Figure 5-7: Embedding flexible conductor with play in order to control the relative displacement of equipments

Figure 5-8: Embedding cut-off switch for controlling equipment's performance

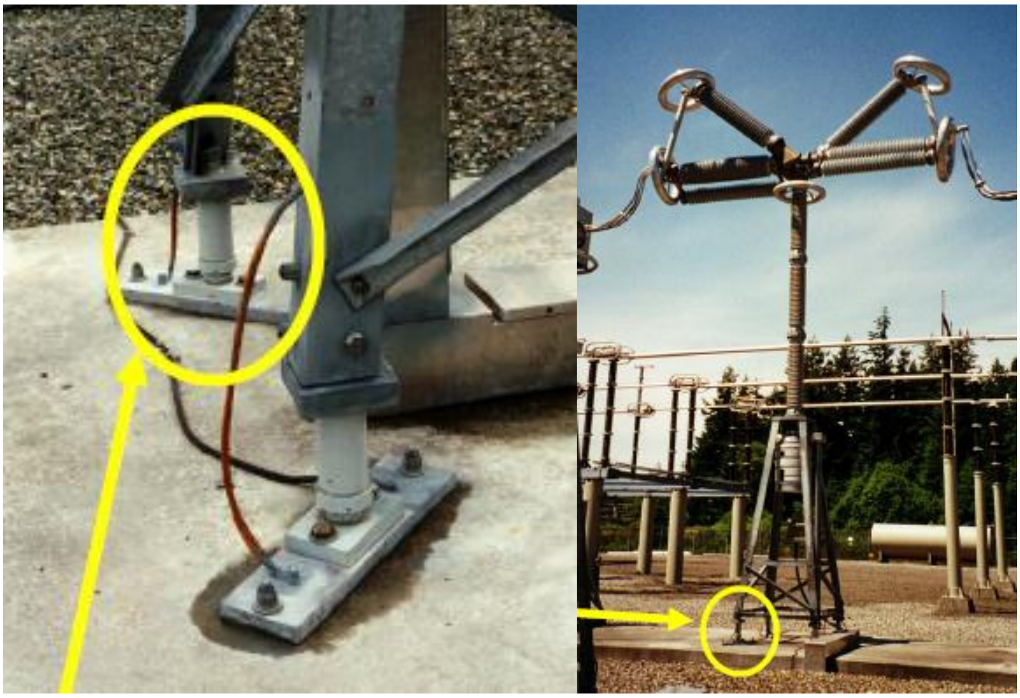


Figure 5-9: Using damper and seismic separator in support structure's leg of equipments to decrease seismic input

Figure 5-10: Batteries shelf bracing for controlling overturn

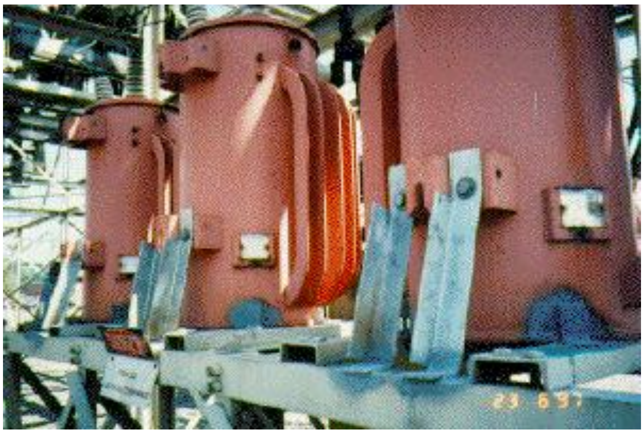


Figure 5-11: Direct bracing of equipments' body for controlling overturn and slippage damage modes

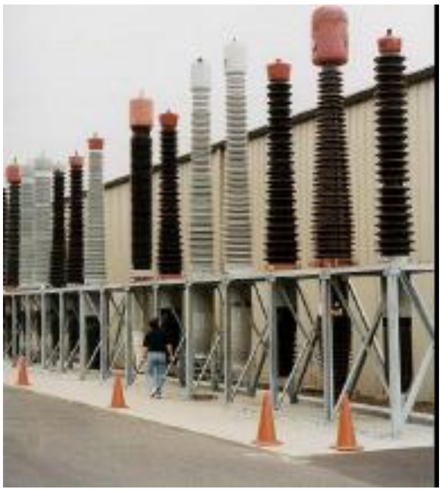


Figure 5-12: Bracing spare equipments in warehouse

5-2-2-3-Buildings

The seismic rehabilitation of buildings is carried out based on seismic rehabilitation instruction (issue #360, President's Deputy of Strategic Planning and Control).

5-2-3-Super-distribution transmission network

The super-distribution transmission network or high-pressure connection lines between power plants and substations include legs and communicative wires. Generally, these networks are built in 63, 132, 230, and 400 kV voltages. High pressure lines are as single-circuit or multi-circuit with telecommunication optical fiber cables or upper protective wire.

There are different high pressure supports and include various shapes as truss supports, frame supports, pre-stressed concrete supports, telescopic metallic supports, and braced truss or frame supports, among which the truss support is the most common. The truss supports, in regards to wires span and inclination angle and ground topography are in light and heavy types and with different elevation supports.

These supports do not have any damage history under earthquake vibration due to light weight and their major damages were due to ground deformations and mountain downfalls. Indeed, wires oscillations in large spans and tension towers would also highly increase the imposed tensile force and in cases would lead to insulators' failure and connections and wire connection hardware to towers.

Table (5.5) shows the list of these equipments presenting observed and possible seismic damage modes, common occurrence reasons of these damage modes and their rehabilitation general method based in damage mode and reason. Seismic damage modes of power plant equipments are not limited to items provided in table (5.4) and the consultant must examine the occurrence possibility of other seismic damage mode based on local conditions and vulnerability studies results, for each case.

Table 5-5: Seismic rehabilitation guide of super-distribution transmission network components

Component	Possible damage mode	Damage reason	Rehabilitation method
Truss supports	Overturn, slippage, and bending Members' damage	High ground settlement due to liquefaction or lateral spreading High ground displacement due to slope slip High ground displacement due to faulting at fault intersecting location Mountain downfall and adjacent structures Adjacent towers overturn Stealing tower parts and creating structural weakness	Ground stabilization with injection or consolidation Reinforcing foundation or embedding piles or micro-piles or converting to a widespread foundation Slope stabilization or tower bracing against slippage with reinforcing foundation or using tendons or creating retaining wall or putting guard at tower Replacing towers located in faulting area Stabilization of downfalls with shotcrete and mesh or using wire screen traps of downfall rocks or structural obstacles at tower upper parts for bracing downfall pieces Physical protection of tower with anti-theft obstacles
Frame and H-shaped supports	Overturn, slippage, and bending Members' damage	High ground settlement due to liquefaction or lateral spreading High ground displacement due to slope slip High ground displacement due to faulting at fault intersecting location Mountain downfall and adjacent structures Adjacent towers overturn Insufficient shear strength Insufficient lateral rigidity of frame	Ground stabilization with injection or consolidation Reinforcing foundation or embedding piles or micro-piles or converting to a widespread foundation or increasing supports buried depth Slope stabilization or tower bracing against slippage with reinforcing foundation or using tendons or creating retaining wall or putting guard at tower Replacing towers located in faulting area Stabilization of downfalls with shotcrete and mesh or using wire screen traps of downfall rocks or structural obstacles at support's upper parts for bracing downfall pieces Frame bracing using internal anchors or external cables
Pre-stressed concrete supports	Overturn, slippage, and bending	High ground settlement due to liquefaction or lateral spreading High ground displacement due to slope slip High ground displacement due to faulting at fault intersecting location Mountain downfall and adjacent structures Adjacent towers overturn	Ground stabilization with injection or consolidation Reinforcing foundation or embedding piles or micro-piles or converting to a widespread foundation or increasing supports buried depth Slope stabilization or tower bracing against slippage with reinforcing foundation or using tendons or creating retaining wall or putting guard at tower Replacing legs located in faulting area Stabilization of downfalls with shotcrete and mesh or using wire screen traps of downfall rocks or structural obstacles at support's upper

Component	Possible damage mode	Damage reason	Rehabilitation method
		Insufficient shear strength	parts for bracing downfall pieces Increasing shear strength by confining with FRP
Telescopic metallic supports	Overturn, slippage, and bending	High ground settlement due to liquefaction or lateral spreading High ground displacement due to slope slip High ground displacement due to faulting at fault intersecting location Mountain downfall and adjacent structures Adjacent towers overturn	Ground stabilization with injection or consolidation Reinforcing foundation or embedding piles or micro-piles or converting to a widespread foundation or increasing supports buried depth Slope stabilization or tower bracing against slippage with reinforcing foundation or using tendons or creating retaining wall or putting guard at tower Replacing legs located in faulting area Stabilization of downfalls with shotcrete and mesh or using wire screen traps of downfall rocks or structural obstacles at support's upper parts for bracing downfall pieces
Truss or braced frame supports	Overturn, slippage, and bending Bracing's cut or play	High ground settlement due to liquefaction or lateral spreading High ground displacement due to slope slip High ground displacement due to faulting at fault intersecting location Mountain downfall and adjacent structures Adjacent towers overturn Low tensile capacity of bracing Displacement of bracing support	Ground stabilization with injection or consolidation Reinforcing foundation or embedding piles or micro-piles or converting to a widespread foundation Slope stabilization or tower bracing against slippage with reinforcing foundation or using tendons or creating retaining wall or putting guard at tower Replacing legs located in faulting area Stabilization of downfalls with shotcrete and mesh or using wire screen traps of downfall rocks or structural obstacles at support's upper parts for bracing downfall pieces Replacing or adding bracings Stabilization of bracing support
Wires, conductors, and optical fibers	Wire cut	Overturn or bending of support Oscillation and resonance in wire	Support stabilization Eliminating wire's resonance oscillation mode by changing its vibration properties, changing wire's internal tension, changing wires separators arrangement
Hardware and connections	Connections and hardware failure	Support overturn and bending Oscillation and resonance in wire	Reinforcing hardware connections and using high strength bolts Replacing hardware with resistant type
Insulators	Detaching from hardware	Support overturn or bending Oscillation and resonance in wire	Reinforcing hardware connections and using high strength bolts Providing sufficient play in insulator's connecting wires

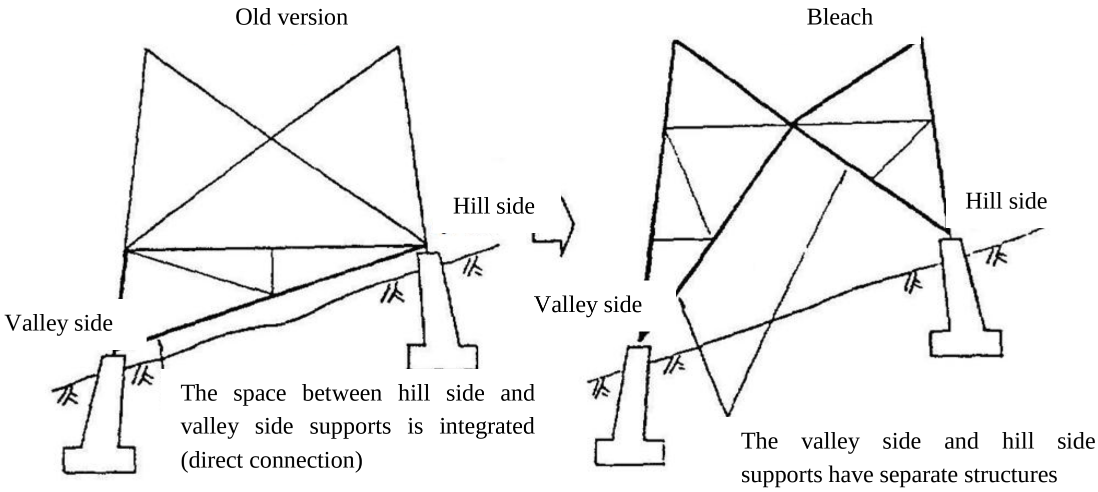


Figure 5-13: Modifying the tower support details in sloped grounds in order to rehabilitate behavior

5-2-4-Urban distribution network

The reviewed components in urban distribution network include non-building structures, equipments, and buildings. These components are separately discussed and a list of them is presented in table (5.6). Also, the distribution network includes 20kV medium-power, 400 and 220V low-power, and urban lighting network. Aerial, ground, and underground voltage conversion substations are tasked with converting medium-power voltages to low-power voltages for urban application.

Figure 5-14: Distribution supports and aerial transformer

Table 5-6: List of power distribution network components

Distribution substations	**Aerial substations (single or couple support)**	Transformer and its connections
		Posts
		LV panels
		Crossarm and insulators of connection to network
	Ground substations	Substation’s building
		Transformer and its connections
		LV and MV panels
	Underground substations	Substation’s building
		Transformer and its connections
		LV and MV panels
Distribution lines	**Medium pressure aerial lines**	Posts (concrete, pre-stressed concrete, wooden, and metallic)
		Crossarm (metallic, wooden, concrete, and composite)
		Insulators (pin, post, suspension, spool, and stay)
		Wires (conductors)
	Low pressure aerial lines	Posts (concrete, pre-stressed concrete, wooden, and metallic)
		Crossarm (metallic, wooden, concrete, and composite)
		Insulators (pin, post, suspension, spool, and stay)
		Wires (conductors)
		Subscribers’ junctions
	Cable ground lines	Cables and connection, path, manholes, and junctions
Road lighting	Cantilevered handles from posts for lighting	
Buildings	Office, control, warehouse, and other buildings	

5-2-4-1-Non-building structures

The non-building structures of distribution networks generally include regular and pre-stressed concrete, metallic, wooden, distribution and lighting supports, handles, aerial wires conducting network, aerial and underground cables along with ducts and manholes.

Table (5.7) shows the list of these equipments presenting observed and possible seismic damage modes, common occurrence reasons of these damage modes and their rehabilitation general method based in damage mode and reason. Seismic damage modes of power plant equipments are not limited to items provided in table (5.6) and the consultant must examine the occurrence possibility of other seismic damage mode based on local conditions and vulnerability studies results, for each case.

Table 5-7: Seismic rehabilitation guide of distribution network non-building structures

Component	Possible damage mode	Damage reason	Rehabilitation method
Regular reinforced concrete posts	Overturn and slippage Bending Bending shear failure	High ground settlement due to liquefaction or lateral spreading High ground displacement due to slope slip High ground displacement due to faulting at fault intersecting location Debris and adjacent structures fall down Adjacent posts overturn Insufficient shear and bending strength of materials	Ground stabilization with injection or consolidation Reinforcing foundation or increasing buried depth Slope stabilization or tower bracing against slippage with reinforcing foundation or creating retaining wall or putting guard Relocating supports located in faulting area Reinforcing weak adjacent structures Relocating supports from debris or building fall down risk area Increasing shear and bending strength using confining with FRP and using its straps Increasing shear and bending strength by confining with reinforced support concrete Increasing shear and bending strength by reinforcing using steel straps Changing support Using stabilizing surface metal web at intersection with ground
Pre-stressed concrete posts	Overturn and slippage Bending Shear failure	High ground settlement due to liquefaction or lateral spreading High ground displacement due to slope slip High ground displacement due to faulting at fault intersecting location Debris and adjacent structures fall down Adjacent posts overturn Insufficient shear strength	Ground stabilization with injection or consolidation Reinforcing foundation or increasing buried depth Slope stabilization or tower bracing against slippage with reinforcing foundation or creating retaining wall or putting guard Relocating supports located in faulting area Reinforcing weak adjacent structures Relocating supports from debris or building fall down risk area Increasing shear strength using confining with FRP and using ring straps Increasing shear strength by confining with steel ring straps Using stabilizing surface metal web at intersection with ground
Wooden posts	Overturn and slippage Bending Bending shear failure	High ground settlement due to liquefaction or lateral spreading	Ground stabilization with injection or consolidation Reinforcing foundation or increasing

Component	Possible damage mode	Damage reason	Rehabilitation method
		High ground displacement due to slope slip High ground displacement due to faulting at fault intersecting location Debris and adjacent structures fall down Adjacent posts overturn Insufficient shear and bending strength of materials	buried depth Slope stabilization or tower bracing against slippage with reinforcing foundation or creating retaining wall or putting guard Relocating supports located in faulting area Reinforcing weak adjacent structures Relocating supports from debris or building fall down risk area Increasing shear and bending strength by reinforcing using steel straps Changing support Using stabilizing surface metal web at intersection with ground
Metallic posts and lighting supports	Overturn and slippage Bending Bending failure	High ground settlement due to liquefaction or lateral spreading High ground displacement due to slope slip High ground displacement due to faulting at fault intersecting location Debris and adjacent structures fall down Adjacent posts overturn Insufficient bending strength of materials	Ground stabilization with injection or consolidation Reinforcing foundation or increasing buried depth Slope stabilization or tower bracing against slippage with reinforcing foundation or creating retaining wall or putting guard Relocating supports located in faulting area Reinforcing weak adjacent structures Relocating supports from debris or building fall down risk area Increasing bending strength by reinforcing using vertical steel straps Using stabilizing surface metal web at intersection with ground
Underground ducts	Wall failure and soil filling in Cracking of duct's shell and opening of contraction gaps Ceiling covering fall down into duct Damages to cables on handles	Insufficient strength capacity of wall's concrete for bearing soil's lateral pressure High ground deformation due to liquefaction or faulting or slip movement and openings' improper design Sharpness of handle of cable seat	Reinforcing duct's concrete wall using internal bracing Adding opening or longitudinal reinforcement in order to remove opening Ground stabilization Providing flexible ground by changing duct's surrounding soil Using seismic gaps at intersection with fault Removing sharpness of cable seat handle by changing or modifying the handle
Underground cable	Detachment of cables from structures or cut at their connection to	High relative deformation between cable and structure or manhole due to excessive	Embedding sufficient freedom and flexibility at cable connection point to structure or manhole using blunt proper

Component	Possible damage mode	Damage reason	Rehabilitation method
	building, canals, or other equipments Cable joints and connections failure	structure's displacement and constrained cable connection to structure High ground deformation due to liquefaction of faulting or slope movement Brittleness and insufficient strength of joints	pipe sleeve, predicting a little excess length and bent in cable or using cables with more strength at required points or intersections with fault Changing or modifying or removing joints, changing force distribution in cable or providing flexibility to soil surrounding the cable Using pipe sleeve
Manhole	Shear failure Bending	Lack of sufficient shear strength Liquefaction	Internal shear reinforcement using ring straps Stabilizing manhole's surrounding soil
Wires, cables, and aerial conductors	Wire cut	Overturn or bending of support Oscillation and resonance in wire	Support stabilization Eliminating resonance oscillation mode by changing its vibration properties or changing wire's internal tension or changing wire's separators' arrangement
Hardware and connections	Connections and hardware failure	Support overturn and bending Oscillation and resonance in wire	Reinforcing hardware connections and using high strength bolts Replacing hardware with resistant type
Insulators	Detaching from hardware	Support overturn or bending Oscillation and resonance in wire	Reinforcing hardware connections and using high strength bolts Providing sufficient play in insulator's connecting wires
Subscribers' junctions	Connection cable cut	Insufficient play in order to damp the relative displacement of building and cable connected to the network	Providing sufficient play in order to damp the relative displacement of building and cable connected to the network

For hard and rock grounds in medium, high, and very high deflections seismic conditions, and concrete posts with 800 to 1200 of nominal power, a buried depth of at least 2.4m are required. For low seismic conditions for a soil with above-mentioned properties, a 1.7m buried depth would suffice. For rehabilitation of posts which are implemented with low depth, the foundation's depth must be increased in which steel reinforcing members could be used beneath the foundation and/or reinforce post's surrounding soil, as shown in the following figure.

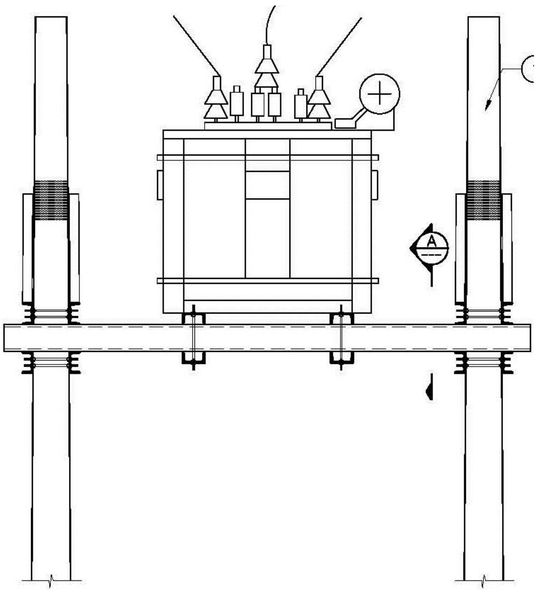
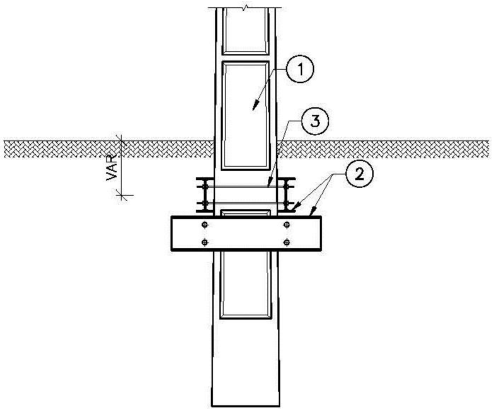


Figure 5-15: Rehabilitation details of aerial transformers of aerial distribution lines using support stabilization method



Reinforcing foundation at ground level by installing steel attachments

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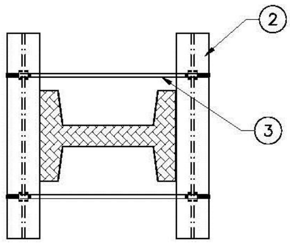

Beam connection method to column

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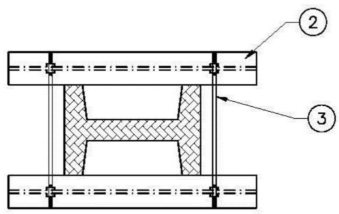

Beam connection method to column

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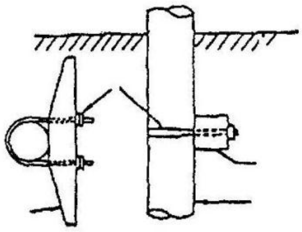


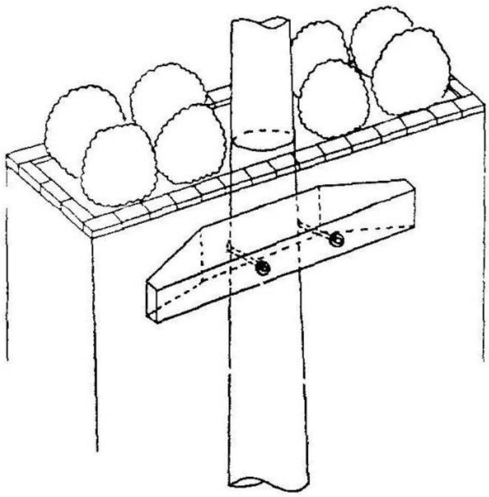


Figure 5-16: Rehabilitation details of aerial distribution lines beams using the stabilization in foundation method

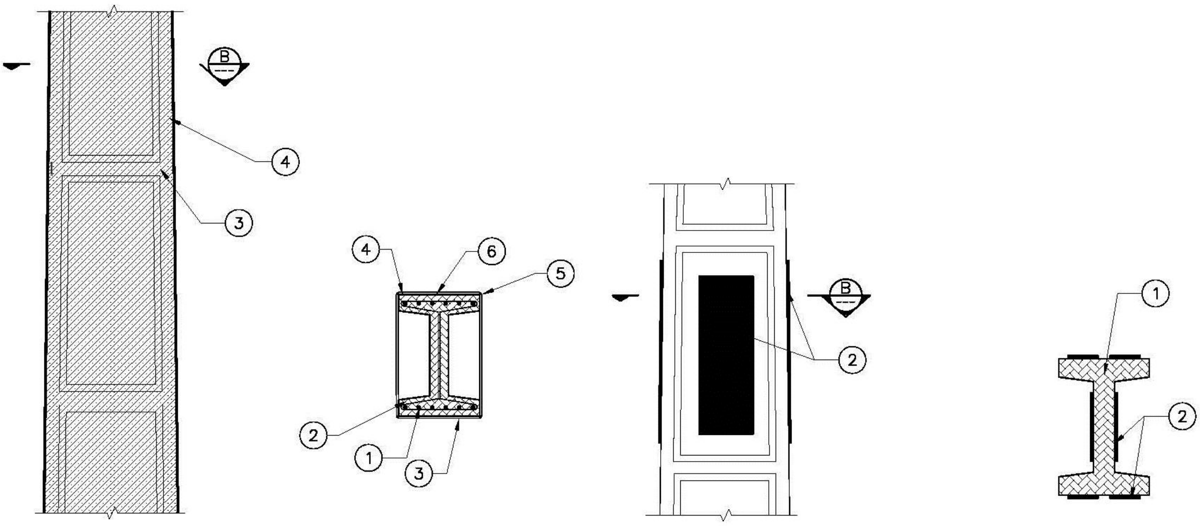


Figure 5-17: Rehabilitation details of aerial distribution lines beams using jacket and/or metal strap

Underground distribution lines should be sufficiently flexible and capable of accepting displacement. Therefore, the above issues could be considered according to the following details as an approach which uses highly flexible pipes throughout the passing course.

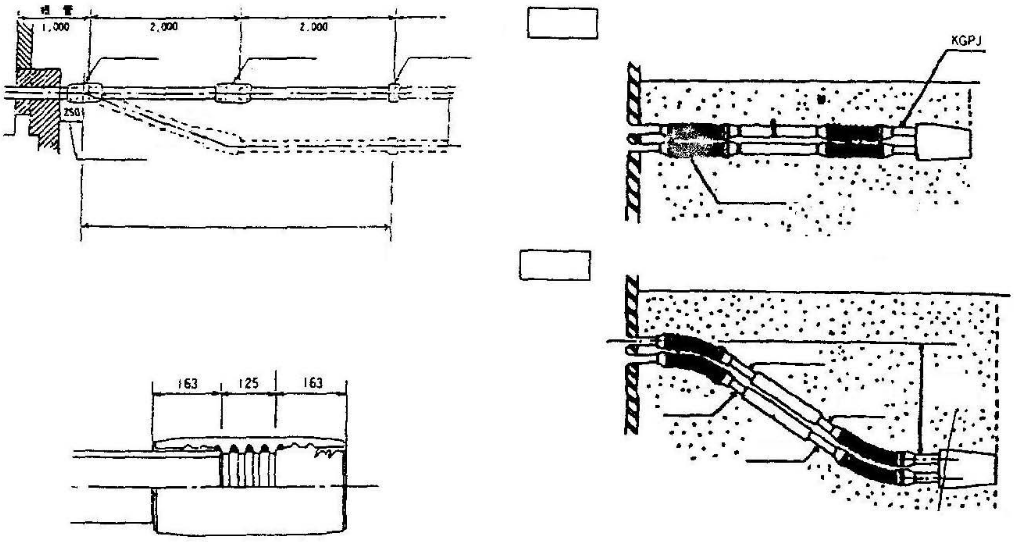


Figure 5-18: Using mild connection in ground transmission power distribution lines

5-2-4-2-Equipments

Totally, the distribution network equipments include aerial transformer, on-ground transformer, low voltage and high voltage panels, and insulators. Table (5.8) shows the list of these equipments presenting observed and possible seismic damage modes, common occurrence reasons of these damage modes and their rehabilitation general method based in damage mode and reason. Seismic damage modes of power plant equipments are not limited to items provided in table (5.7) and the consultant must examine the occurrence possibility of other seismic damage mode based on local conditions and vulnerability studies results, for each case.

Table 5-8: Seismic rehabilitation guide of distribution network equipments

Component	Possible damage mode	Damage reason	Rehabilitation method
On-ground transformer	Overturn and slippage Failure or oil leakage from insulator Radiator detachment Oil tank detachment	Uncontrolled slippage due to lack of proper lateral bracing or being placed on wheels or rail Uncontrolled vibrations of insulator Lack of lateral bracing system Lack of lateral bracing system	Replacing wheel with anchored seat Attaching with anchor rod to foundation Lateral metallic support attached to foundation Replacing ceramic insulator with composite Reinforcing cap's connection against leakage Embedding proper lateral bracing in support Embedding proper lateral bracing in transformer's body Embedding proper lateral bracing in support Embedding proper lateral bracing in transformer's body
Aerial transformer	Overturn Bending Oil leakage	Transformer's weak connection to base Base's weakness and damage Damages in support Weakness in transformer's connection bolts to base	Reinforcing transformer's connection and bracing to base Reinforcing base Replacing bolts with high strength ones Increasing base's upper or lower or lateral profile
Low pressure and medium pressure panels and booths	Overturn	Lack of lateral bracing system	Connecting with anchor rod to floor or ground Lateral connection to wall or base Connecting to ceiling or bases connecting beam Connecting panels to each other

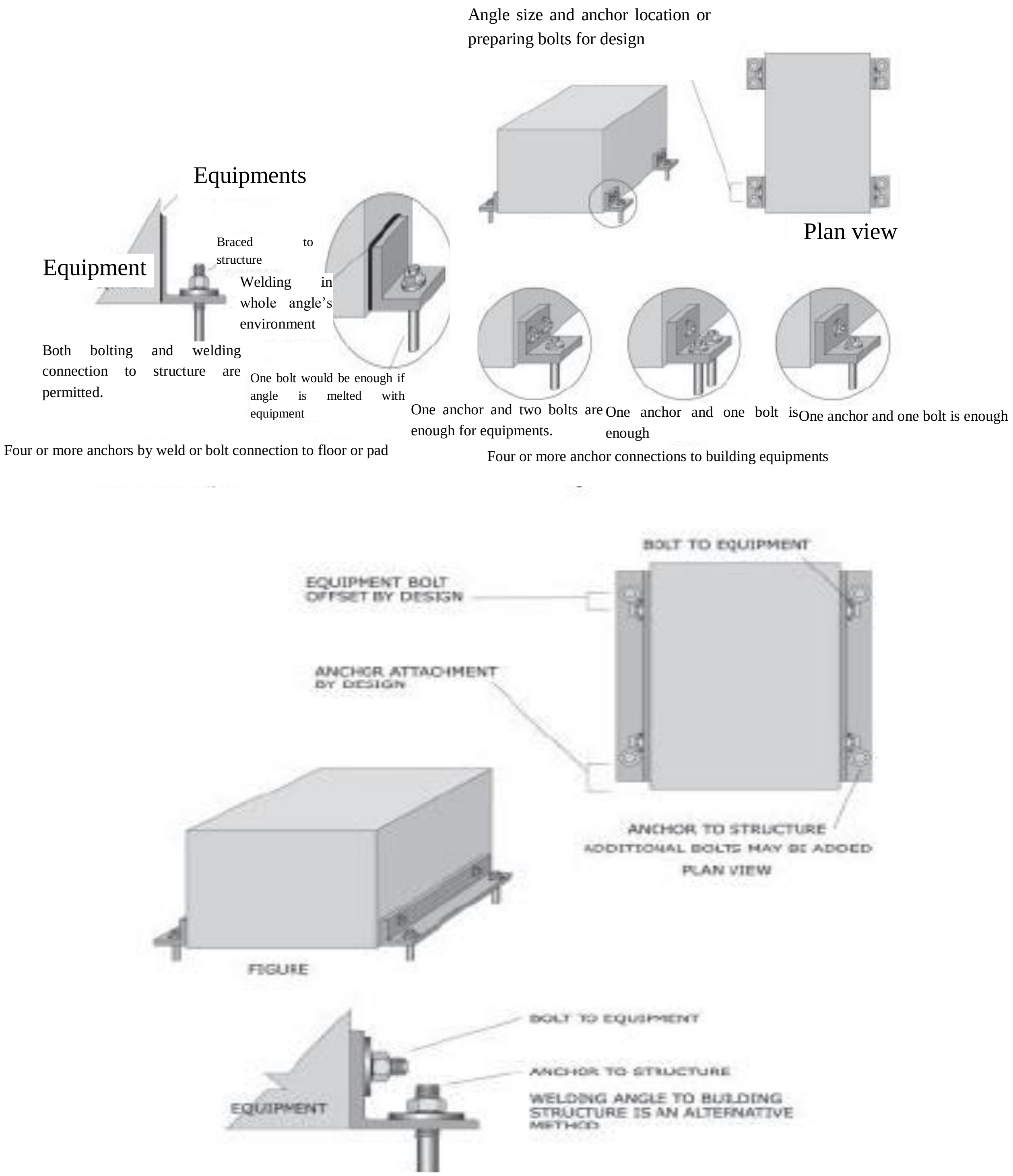


Figure 5-17: Examples for rehabilitation details of panels' anchor

5-2-4-3-Buildings

Medium and low voltage substations are usually constructed as on-ground or underground. Generally, the buildings of on-ground substations are built in two type; single-storey with monumental materials and concrete or metallic cradling, and two-stories with concrete or metallic frame.

Some of these substations are single-storey with a basement in order to provide connection to underground cable network or canals or cable ducts. The underground substations are constructed where there is not enough space and possibility to construct on-ground substations. Usually, they have frames with concrete or monumental walls.

The seismic rehabilitation of these building structures is carried out based on seismic rehabilitation instruction (issue #360, President's Deputy of Strategic Planning and Control).

Appendix

Appendix 1-Classification of subscribers of power transmission network

In this guideline, types of intended subscribers involve home utilization, public utilizations, agricultural utilizations, industrial utilization, commercial utilizations, lighting and special subscribers. In following, above-mentioned subscribers are described summarily.

Power branching for home utilizations is applied for a branch that merely established for operation of ordinary home apparatus and equipments in residential units.

Power branching for public utilization is applied to a branch that is used for public services. Types of public subscribers can be classified as following.

- ministries and their subsidiary offices, the Legislative, the Judiciary, Foundation of Martyrs and Veterans Affair,Foundation of the Oppressed and Disabled, Foundation of the 15 Khordad, municipalities and all governmental firms and organizations that aren't administered as company (such as Organization of Hajj, Endowment and Benevolent Affairs, Organization of Management and Planning, Environment Protection Organization, Agricultural-Jihad organizations of provinces, customs, Port & Maritime Administration, I.R. Iran Civil Aviation Organization), Joint consumptions of non-residential building complexes, mausoleums, cemeteries and ghasalkhanehs.
- all qualified research institutions and research centers with valid licenses from formal authorities, Sale positions of petroleum products, Governmental sanitary and remedial centers such as hospitals, clinics, Centers of medical recognition, Medical centers, all beneficence institutions and centers, of Red Crescent and Imam Khomeini Relief Committee, residential complexes and towns, gardens, green areas of cities and consumptions related to beautification of cities.
- cultural centers (such as libraries, museums, registered historical sites), Broadcasting, cinemas, education and upbringing centers (such as kindergartens, preschools, schools, universities, educational hospitals, Career and Technical Education centers, schools, seminaries) student dormitories, student camps, Islamic Development Organization, mosques, Hoseiniehes, tombs of martyrs, shrine monuments and holy places of recognized religious minorities, sport centers, Disabled welfare and patronization centers, peoples with disabilities and elders, baths and clubs.
- military and police garrisons and centers
- rural and urban drinking water pumpage and refineries, sewage collection refineries and networks, drainage wells related to water and sewage centers, jungle parks and non-traditional bakeries
- small sanitary and medical centers such as medic recognition, medication centers, medical centers and physician clinics
- traditional bakeries

Agricultural power branching is applied for branching that uses power for pumpage of surfacial and underground waters or further pumpage of water for production of crops and also have operation licenses from Regional Water corps. Agricultural subscribers can be divided in two groups including water pumpage for irrigation (agriculture, further pumpage, pressurized and gravity irrigation) and water pumpage for production of crops (gardening, animal husbandry, reproduction and culture of aquatic in internal waters).

Industrial power branching is applied for branching that is used for operation of big industries and plants (such as production of mushroom, fishery, culture of caterpillar, reproduction and culture of aquatic in internal waters, poultries and animal husbandries) and small industries and production guilds.

Commercial power branching is applied for branching that is used generally for market places in non-production centers and also all supply centers. According to International Standard Industrial Classification of All Economic Activities (ISIC), various types of commercial subscribers can be presented as following:

- Wholesales such as wholesale of all products such as foods, home appliances, office supplies, etc.
- retails such as retailing of all products such as groceries, carnages, supermarkets, bookstores, boutiques, drugstores and cosmetics stores

Table 1-Classification of special subscribers

	Subscriber Type	Inclusive organizations	definition of activity
1	staff	province general governors governments municipalities crisis management organizations unexpected accidents and disaster staff Presidency of The Islamic Republic of Iran communication and information systems	planning and dispatching of received forces and supplies from various sources, procurement and collection of reliefs, suitable maintenance and distribution of facilities to relief forces and people, planning and coordination for supplying facilities to inhabit people and for damaged regions on the basis of precedence, supplying required communications for relief organizations and institutions, supplying required communications for damaged people
2	power support	Regional Electric Companies power transmission companies	supplying power to damaged regions to endure relief operation day and night and prevent horror of damaged people from darkness, detection of damaged electrical facilities, technical inspection of all supply lines, equipment and connections related to subscribers in damaged regions and try to reestablish power transmission system
3	political and military	Organizations and administrations of information and security General Command of Armed Forces of the Islamic Republic of Iran military and police centers centers of aerial and armed forces	
4	auxiliary	hospitals, emergency centers and clinics, Red Crescent populations, organizations of firefighting and safety services of cities, Road & Transportation offices, Relief committees	specialized search to find individuals, required actions to bring out damaged peoples, performing basic critical actions in incident places, remedial actions, supplying sanitary forces in provisional places and sanitary controlling of damaged areas, halting and quenching fire, supplying required safety for relievers, recognition and debris removing of relieve paths, supply and distribution of transportation machines to relief and remove debris
5	critical services	The National Iranian Oil Products Refining& Distribution gas companies water and sewage organizations Fruits, Vegetable and Agricultural Products Wholesale Markets Organizations	performing basic critical actions with coordination of emergency teams, compulsive housing and providing necessities and primary utensils of damaged people, supply and distribute fuel and oil products, water for drinking and other consumption and also food

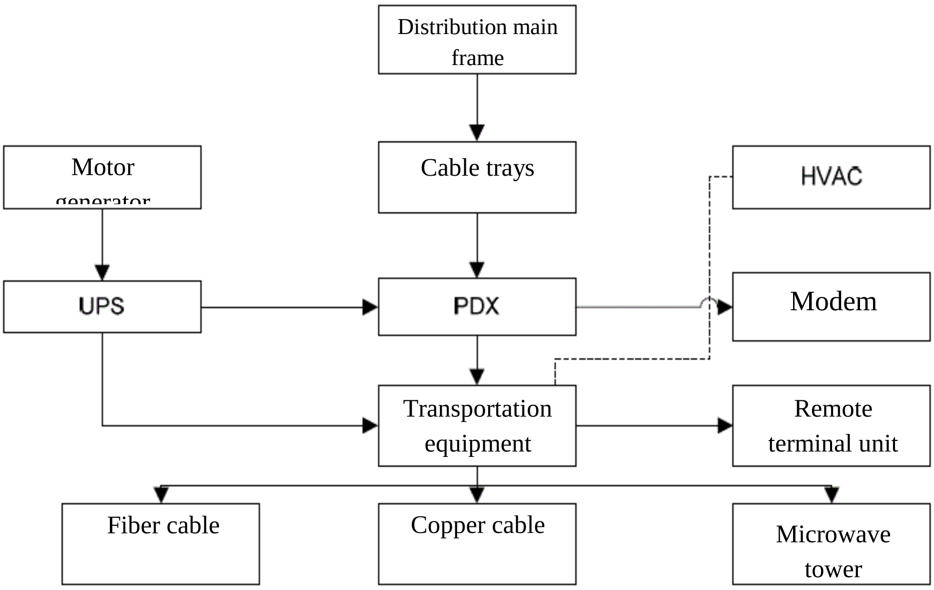


Figure 1-Communication equipment in control center or secondary stations

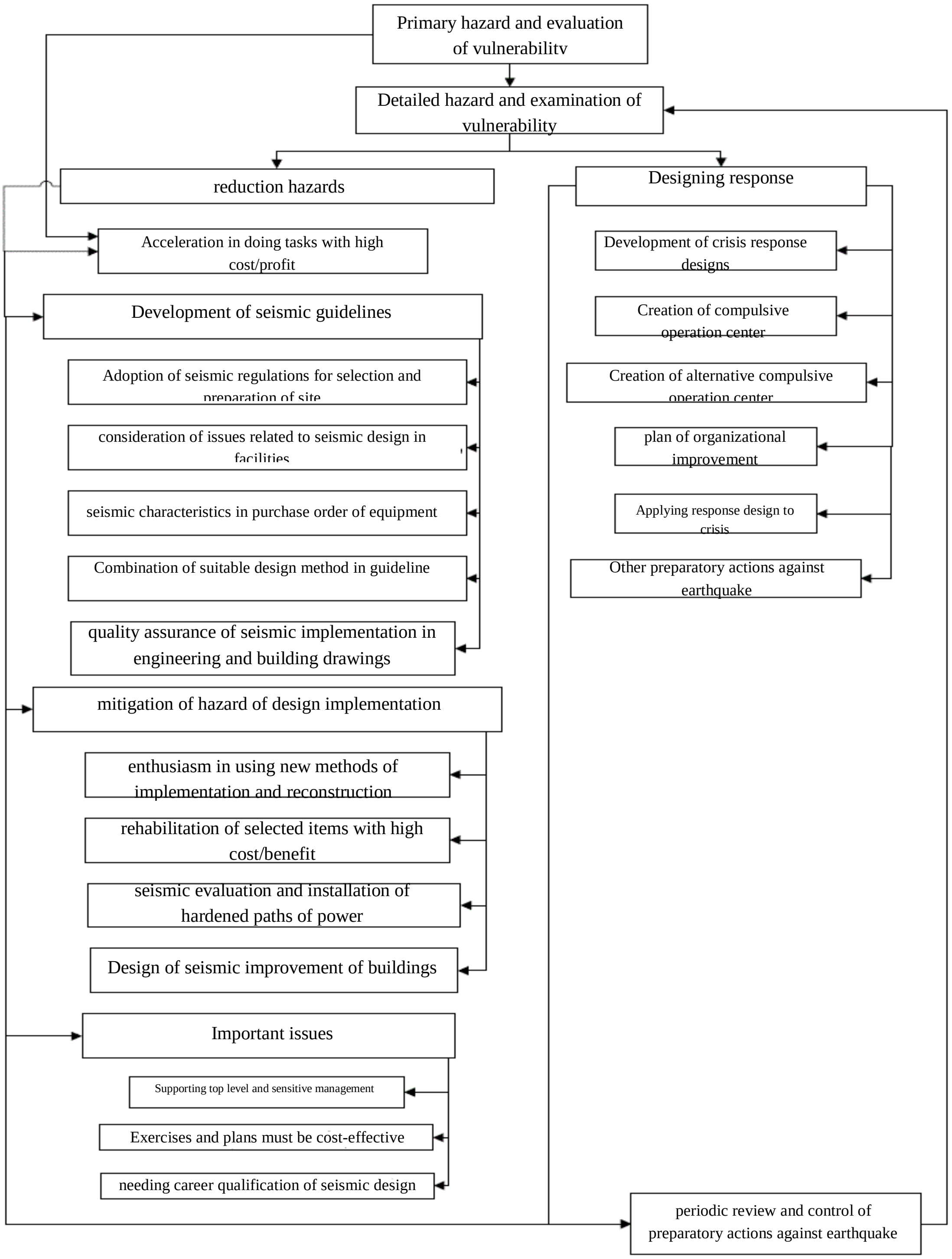


Figure 2-Flowchart of development and implementation steps of preparatory plan against earthquake

Appendix 2: Samples of fragility function

2-1-Cable fragility curves

2-1-1-Methods of calculation of fragility curves

(1)Definition of damage modes for buried cable systems

a) Major fragility

Major fragility of cables occurs when structural response under earthquake load exceeds major fragility mode

b) Moderate fragility

Moderate fragility occurs when cable structural response under earthquake load is between major and minor fragility mode

c) Minor fragility

Moderate fragility occurs when cable structural response under earthquake load is lower than major and moderate fragility mode

(2)Definition of fragility occurrence probability

If R_{major} is the critical strength of structural component in major fragility mode and $R_{moderate}$ is related to intermediate fragility mode, fragility occurrence probability for different fragility mode can be computed through following equation when load S is applied on structure:

$$\begin{aligned} &P[\text{major damage}] = P[R_{major} < S] \\ &P[\text{moderate damage}] = P[R_{\min or} \le S \le R_{major}] = 1 - P[\text{major damage}] - P[\text{minor damage}] \\ &P[\text{minor damage}] = P[R_{\min or} > S] \end{aligned} \tag{1}$$

(3) Calculation method of fragility occurrence probability

If structure strength R and applied load S are random variables, fragility occurrence probability is calculated through following method. It is assumed that Z is random variable with mathematical expectancy E[Z] and standard deviation σ_Z. So, fragility occurrence probability is given by following relation:

$$\begin{aligned} P[R < S] &= P[Z < 0] = P[E(Z) + z\sigma_Z < 0] = P\left[z < -\frac{E[Z]}{\sigma_Z}\right] = \\ &= P[z < -\beta] = \Phi[-\beta] = 1 - \Phi[\beta] \end{aligned} \tag{2}$$

Where

φ is function of standard time distribution and β is obtained from relation 3:

$$\beta = \frac{E[Z]}{\sigma_Z} = \frac{E[R] - E[S]}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{3}$$

Where

β is safety index related to design on the basis of reliability.

(4) Descriptive example of fragility curves

Fragility curve is defined as fragility occurrence probability $P[damage]$ for expected load of $E[S]$. Figure 3 shows fragility curve for each fragility mode.

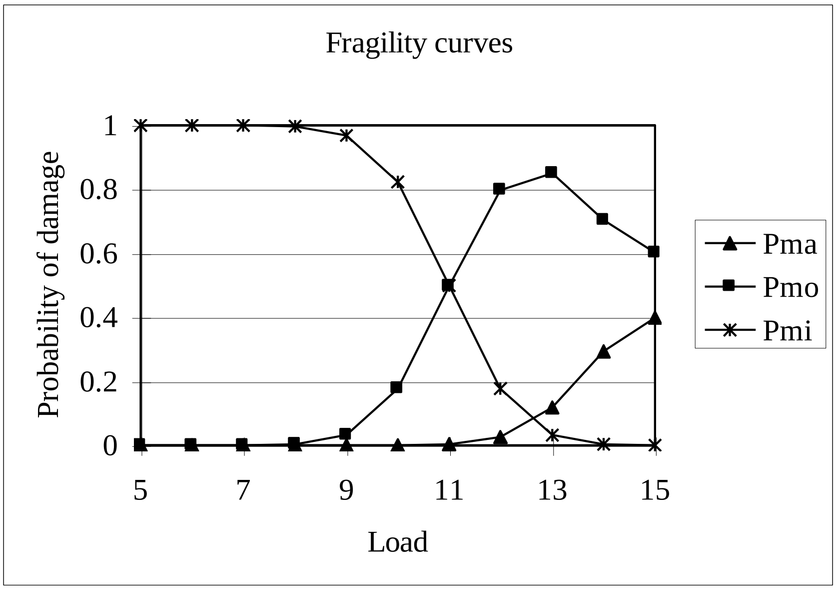


Figure 3-Descriptive example of fragility curves

2-1-2-Structural components of buried cables and associated structures

Fragility mode of each structure is the main index of its final strength. Table 2 presents summary of structural models of underground cables, associated underground structures and their connection to buildings.

Variation factor of structural components is assumed to be between 10 and 30 percent that gives conservative estimation of axial strength of underground structures, because there isn't enough information regarding axial behavior of these structures under earthquake effect.

a) Buried cable

Maximum compressive and tensile strain against alternative loads such as earthquake indicates critical strength. In the case of intersection with fault, tensile strength of cable plays more important role. This mode is critical mode.

b) Underground cable connected to building

An underground structure involves various conduits, manholes and containers. Entry or exit cable from underground structure may be failed in tensile mode or due to settlement or movement of structure. If underground structure doesn't situated on pile, vertical settlement don't cause considerable problem but horizontal movements are important in the cases such as passage across fault.

c) Connection of underground cable to structure

In the case of vertical settlement between structure and surroundings soil, huge bending is imposed on cable that may lead to cable bucking. In this regard, bending angle represent ultimate strength of cable connected to building.

Experimental result of cable bending by ADEP in 1986 presented values of cable strength in terms of bending angle. Conservatively, about 2.5 degree is considered corresponding to minor fragility mode and 12 degree is considered as extensive fragility mode. Table 2 represents intermediate values and variation factor of these two fragility mode.

Table 2-Structural models and their strength for buried cables

fragility mode	**fragility state**	**unit**	**Cable strength**			
			intermediate		**variation factor**	
			Rminor	Rminor	dRminor	dRminor
fragility due to waves	alternative strain	%	1	10	0.1	0.2
fragility due to horizontal extension	strain	%	10	30	0.2	0.3
fragility due to vertical settlement	short curvature	degree	2.5	12	0.2	0.3

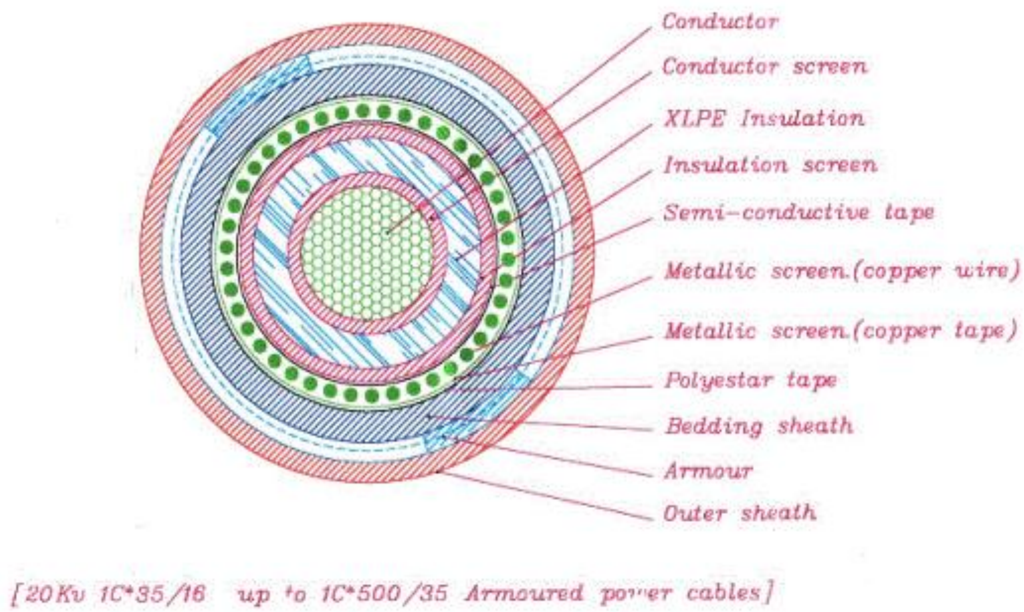


Figure 4-Section of 20kV buried cable

Cables have various sections. Figure 4 shows a sample of cable section that has copper core. Cable rupture occurs due to yielding this core or cracking of its outer sheath. Figure 5 shows a sample of cable stress-strain curve. However, this curve is different depends on cable insulation system. In this model, cable diameter for voltages 63, 20 and 0.4 kV is considered to be equal to 10, 5 and 2 cm, respectively.

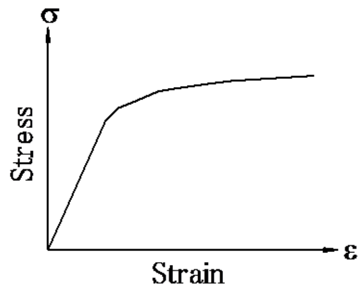


Figure 5-Schematic cable stress-strain curve

2-1-3-Load models

Table 3 represent summary hazards due to ground movements that can damage cable, together with required seismic parameters for their evaluation and recommended methods to obtain these parameters and required geotechnical characteristics for evaluation of spontaneous hazard. Cable evaluation method must be capable to consider all resources and potentials of ground deformation.

Table 3-Seismic parameters of cable evaluation

Hazard	Earthquake parameter	resource	geotechnical parameter
Ground transient movement			
total quake	PGA, PGV, accelergraph	SHA	condition and depth of soil and VS
direction effect of near focus	fault distance	SHA, fault map	fault type, rupture direction and mechanism
magnification		SHA	local condition of soil and VS
Permanent ground displacement			
faulting	magnitude and length	geology	fault type and strike
liquefaction	PGA, magnitude	SHA	soil type, density, layer thickness and groundwater level
lateral expansion	PGA, magnitude and distance	SHA	topography, soil type, strength and groundwater level
dip sliding	PGA, accelergraph	SHA	topography, soil type, strength and groundwater level
settlement	PGA	SHA	topography, soil type, strength and groundwater level

SHA: Seismic hazard analysis system
PGA: maximum ground acceleration
PGV: maximum ground velocity

2-1-6-Cable fragility curves in various fragility modes

a)Cable fragility curves due to wave

Ground strain due to earthquake is calculated as following:

$$\varepsilon_G = \frac{S_V}{V_s} \qquad (4)$$

Where, S_V and V_S are velocity response spectrum and shear wave velocity in ground level, respectively. Figure 6 shows one sample of cable fragility curve due to wave effect in which, cable limit strain in extension state between minor and intermediate mode and between intermediate and extensive mode are assumed to be 1% and 10% respectively.

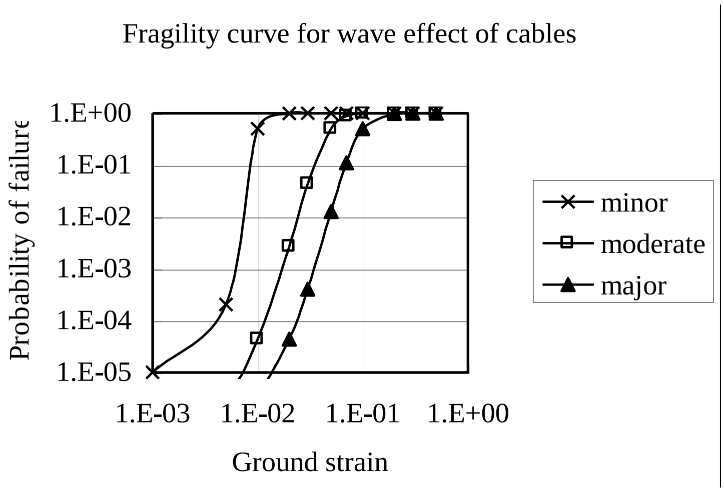


Figure 6-Cable fragility curve due to effect of earthquake waves

b) Cable fragility curves in settlement due to liquefaction

Settlement due to liquefaction for h between 0 and 2.5 m in the distance W with spring module K and bending hardness EI is assumed to be 1.57kgfcm and 30.68×10^6 kg/cm^2.

In this case, critical angles of cable for minor, intermediate and extensive modes are 2.5, 6 and 12 degrees respectively. For instance, fragility curves related to 63 kV, 20 kV and 0.4kV cables are shown respectively in figures 7 to 9.

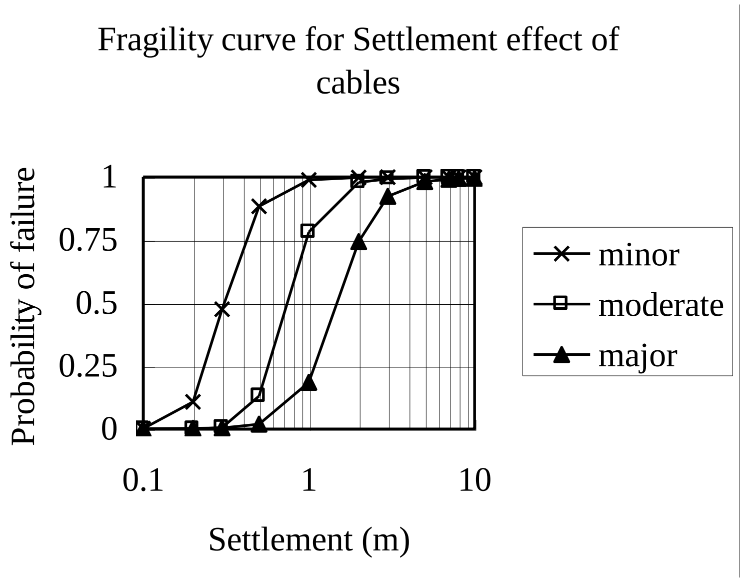


Figure 7-Fragility curve of 63kV cable due to settlement

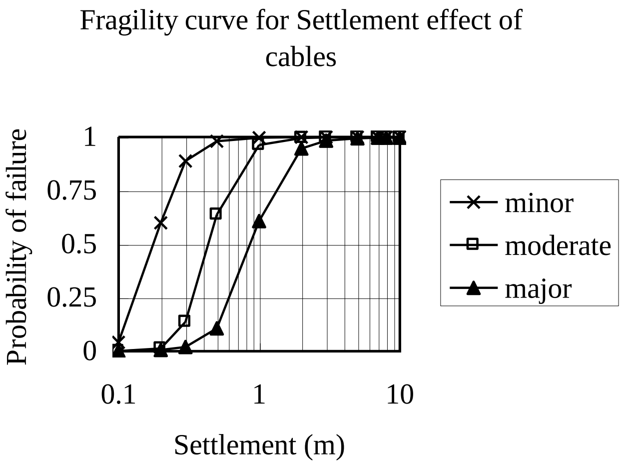


Figure 8-Fragility curve of 20kV cable due to settlement

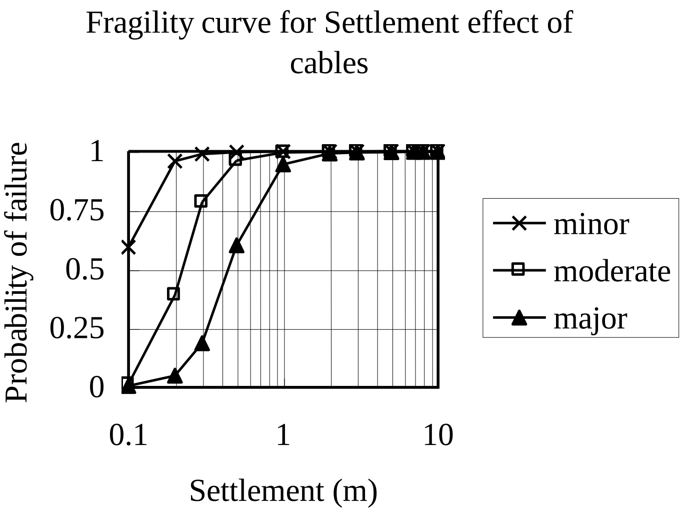


Figure 9-Fragility curve of 0.4kV cable due to settlement

c) Curves of cable fragility due to intersection with fault

Horizontal displacement of fault is considered to be between 0 and 10 m. Parameter values of E2 and q are equal to $1\times10^5 N/cm^2$ and 2 N/cm. Obtained fragility curve for 63 kV, 20 kV and 0.4kV cables are shown respectively in figures 10 to 12.

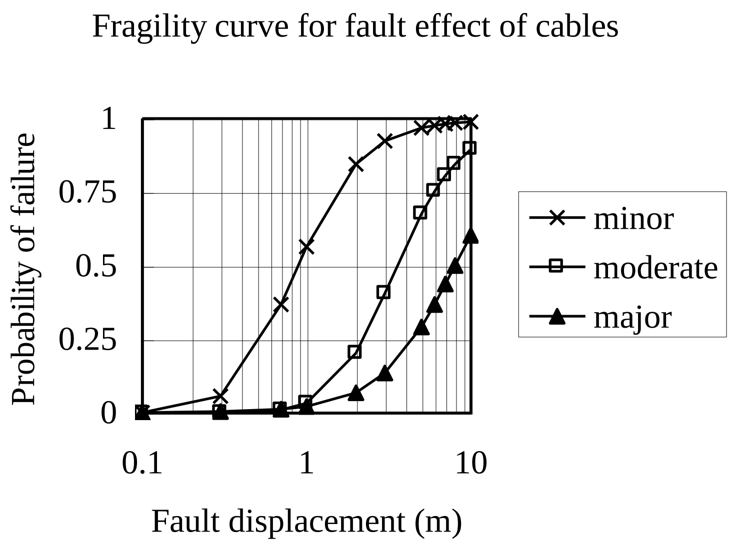


Figure 10-Fragility curve of 63kV cable in intersection with fault

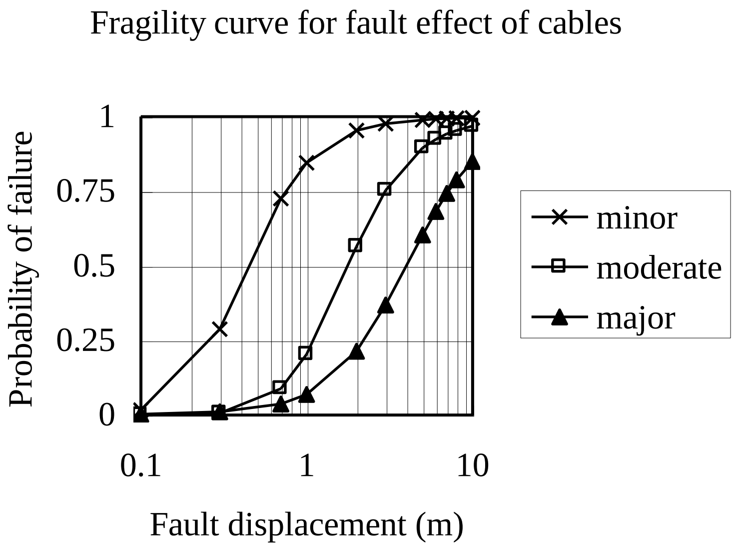


Figure 11-Fragility curve of 20kV cable in intersection with fault

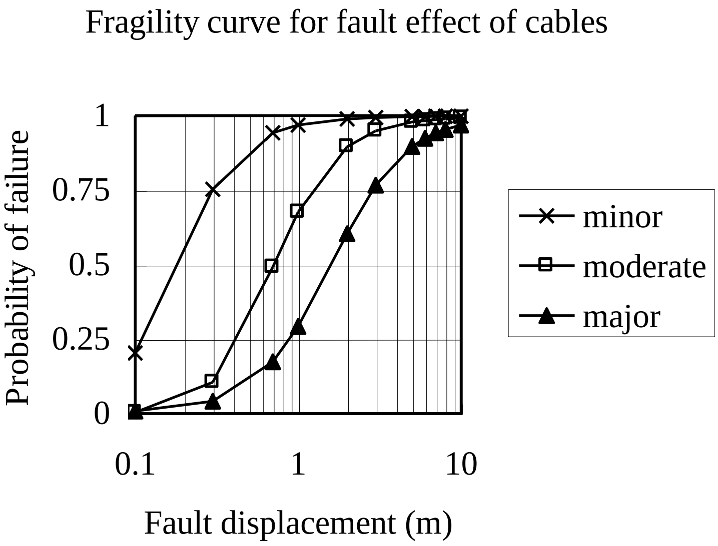


Figure 12-Fragility curve of 0.4kV cable in intersection with fault

d) Cable fragility curves due to slope sliding

Width of sliding area W and elongation N are the main parameters in estimation of cable fragility probability resulted from elongation due to slope sliding. W is directly related to slope condition. For simplicity, effective length L obtained from analysis related to intersection with fault is considered. Figures 13 to 15 show fragility curves for 63 kV, 20 kV and 0.4kV cables.

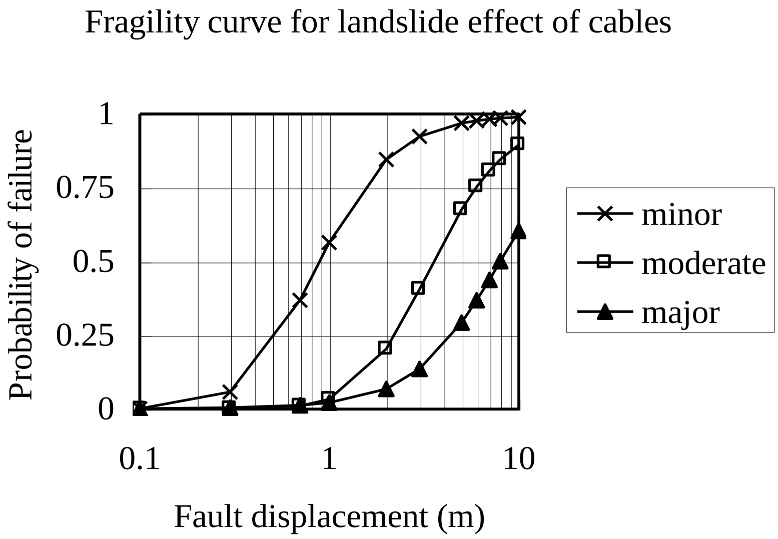


Figure 13-Fragility curve of 63kV cable due to slope sliding

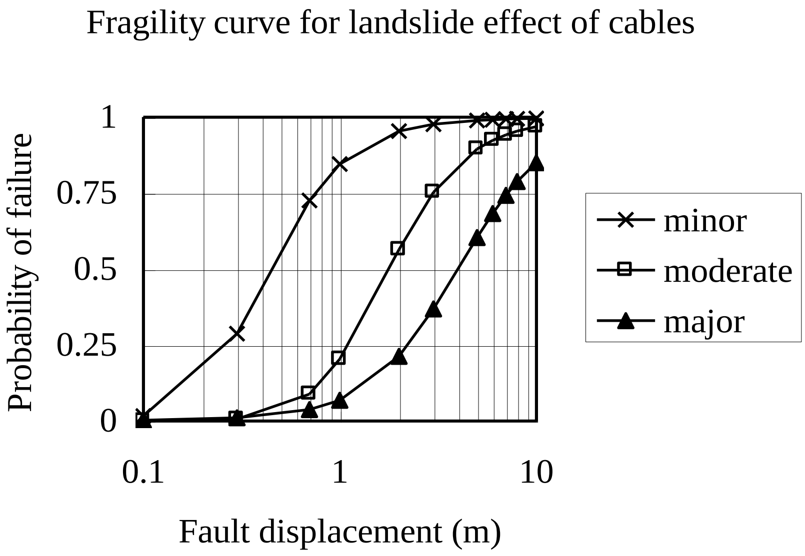


Figure 14-Fragility curve of 20kV cable due to slope sliding

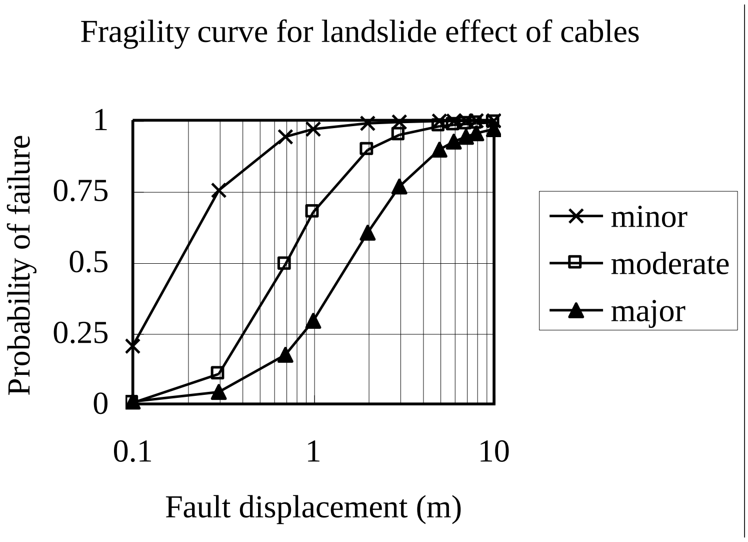


Figure 15-Fragility curve of 0.4kV cable due to slope sliding

2-2-Fragility curves of power posts

2-2-1-Introduction and review of previous studies

Power posts have shown vulnerable behaviour in pervious earthquakes. Transformer is the main member of posts to be investigated with regard of fragility state.

Previous earthquakes have shown that porcelain bushings are the most vulnerable member of transformer. Even in earthquakes of maximum acceleration of 0.3g, oil leaking occurred that lead to de-energizing transformer.

In some posts, several fragilities occurred due to interaction of earthquake effects and internal loads.

Due to bushing modelling in experiments individually, some discrepancies are appeared in bushing behaviour in experiments regarding actual behaviour in earthquake while in practice, collection of transformer and bushing act together.

In analytical model of busbar connection, it is shown that flexibility of connecting spring in yielding state lead to damping and decrease of vibration amplitude. These results are presented as dimensionless ratios. Numerical studies have been performed to investigate bending hardness effects, cable damping and various parameters of earthquake and dimensionless ratios of response have been presented as function of interaction parameter that represents slack values in flexible busbar system.

Another analytical study showed that transformer structure is more flexible than what is conceived. Moreover, transformer flexibility decrease drastically in a section that connects with bushing. Dynamic amplification is occurred in two frequencies.

Transformer flexibility affects bushing behaviour and this is predominately due to flexibility of upper sheet of transformer.

One objective was to obtain comprehensive behaviour for all types of transformer and bushing. For this end, bushing was modelled individually and together with transformer and linear dynamic analyses were performed under accelergraph effect of an earthquake. Another objective was to obtain fragility function of electrical equipment and recommendations have been proposed for major, intermediate and minor fragility modes.

2-2-2-An introduction to fragility curve of posts

In recent years, many fragility curves have been presented for post equipments which the most important of them are UWG in 1999 and HAZUS and FMEA in 1999.

a) UWG fragility curves 0.5

These fragility curves are based on four main parameters including minimum acceleration associated with initiation of fragility and accelerations associated with 16, 50 and 84 percent of fragility. These parameters have been estimated for various equipments. For example, table 4 presents these parameters for single-phase 230kVtransformer (TR1), three-phase 230kVtransformer (TR2), single-phase 500kVtransformer (TR3) and three-phase 500kVtransformer (TR4). Curves of figures 16 and 17 are presented based on normal distribution N ($m_1\sigma_1$) for probability lower than 0.5 and N ($m_2\sigma_2$) for probability higher than 0.5, where m is mean value associated with 50 percent values in tables. σ_1 and σ_2 values are obtained with assumption that m-σ_1 is equal to 16 percent and m+σ_2 are equal to 84 percent occurrence probability. Fragility probability for all acceleration values lower than mean values associated with initiation of fragility is assumed to be zero. Examples of these fragility curves are presented in figures 16 and 17.

Table 4-Fragility parameters of various 230 and 500 kV transformers

UWG Class	Equipment Description	Failure Mode	84th %(g)	50th % (g)	16th % (g)	Minimum (g)
TR1	1- phase 230 kV transformer	1 main porcelain gasket leak	0.75	0.50	0.25	0.25
		1 main porcelain break	1.15	0.85	0.65	0.50
		major break in radiator	1.35	0.85	0.65	0.50
		anchorage failure	1.60	0.95	0.80	0.75
		transformer overturn	1.80	1.50	1.40	0.90
TR2	3- phase 230 kV transformer	1 main porcelain gasket leak	0.75	0.50	0.20	0.20
		2 main porcelain gasket leaks	0.85	0.50	0.30	0.20
		3 main porcelain gasket leaks	0.95	0.50	0.40	0.20
		1 main porcelain break	1.15	0.85	0.55	0.20
		2 main porcelain breaks	1.25	0.85	0.65	0.35
		3 main porcelain breaks	1.35	0.85	0.75	0.50
		major break in radiator	1.35	0.85	0.65	0.50
		anchorage failure	1.60	0.95	0.80	0.75
		transformer overturn	2.25	1.50	1.15	0.90
TR3	1- phase 500 kV transformer	1 main porcelain gasket leak	0.70	0.45	0.20	0.10
		1 main porcelain break	1.05	0.75	0.50	0.10
		major break in radiator	1.25	0.75	0.55	0.40
		anchorage failure	1.60	0.95	0.80	0.75
		transformer overturn	1.80	1.50	1.40	0.90
TR4	3- phase 500 kV transformer	1 main porcelain gasket leak	0.65	0.40	0.15	0.10
		2 main porcelain gasket leaks	0.75	0.40	0.20	0.10
		3 main porcelain gasket leaks	0.85	0.40	0.30	0.10
		1 main porcelain break	0.95	0.65	0.35	0.10
		2 main porcelain breaks	1.05	0.65	0.45	0.10
		3 main porcelain breaks major	1.15	0.65	0.55	0.10
		break in radiator	1.20	0.70	0.50	0.40
		anchorage failure	1.60	0.95	0.80	0.75
		transformer overturn	1.80	1.50	1.40	0.90

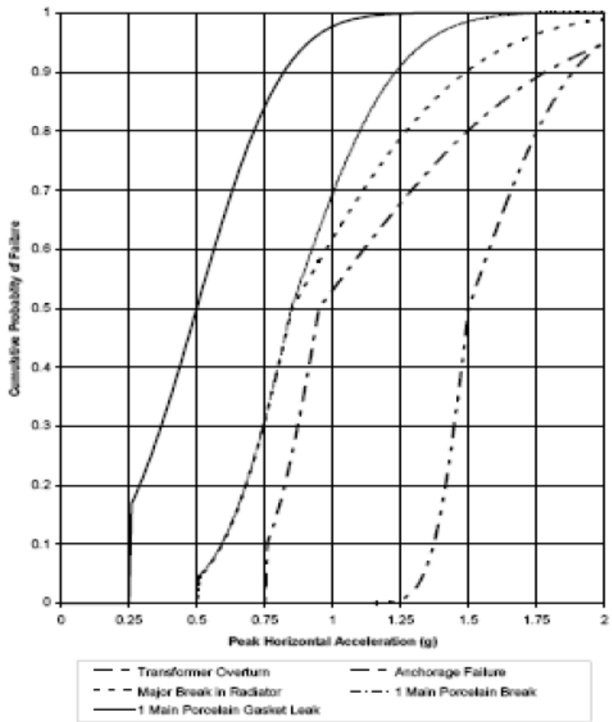


Figure 16-UWG fragility curves for single-phase 230 kV transformers

b) HAZUS fragility curves

In this section, fragility curve of production, transmission and distribution equipments are investigated in terms of fragility modes. These curves have been developed for various electrical systems and indicate that if there is a fragility probability in fragility mode for any input acceleration. These curves have been prepared in two modes of standard and braced equipments that are associated with voltages of 138 to 765 kV or more for transmission facilities and 34.5 to 161 kV for distribution equipments. Classification of these equipments have been performed in three classes namely high voltage for 350 kV and more, intermediate voltage for 150 to 350 kV and low voltage for 34.5 to 150 kV that are recognized as 500 kV, 230 kV and 115 kV posts respectively.

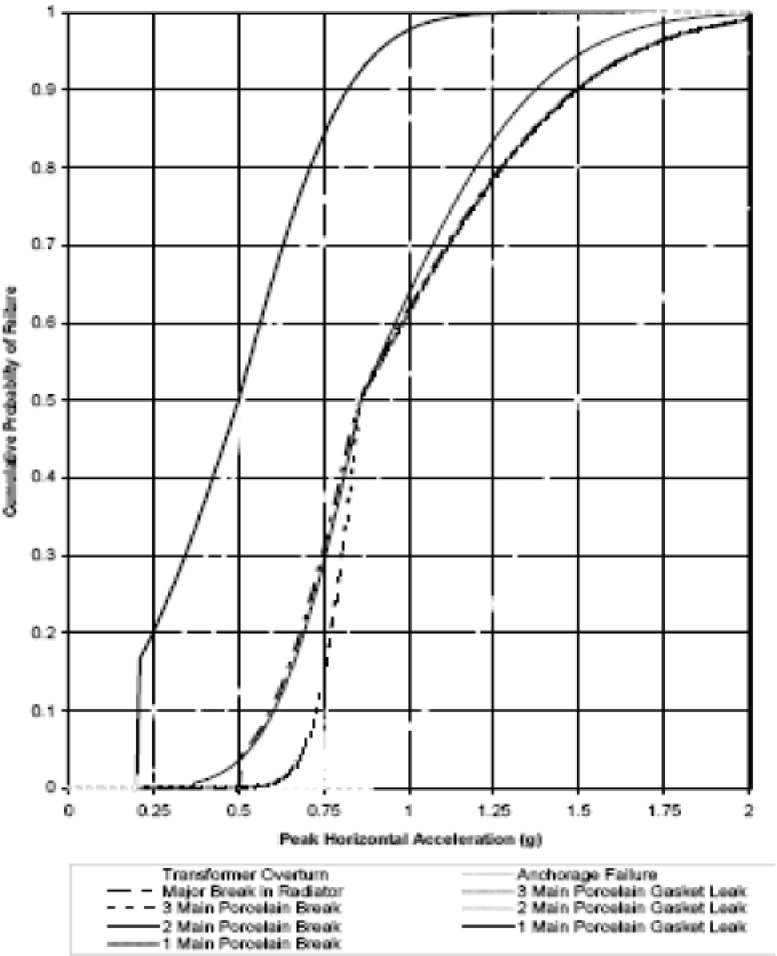


Figure 17-HAZUS fragility curves for three-phase 230 kV transformers

c) Definition of fragility mode in HAZUS

Power production, transmission and distribution equipments are vulnerable under PGA and sometimes PGD and their fragility modes are defined on the basis of these two parameters. Here, five fragility mode are defined for power facilities including ds1: without fragility, ds2: minor, ds3: intermediate, ds4: extensive and ds5: total destruction. In the case of power systems and distribution networks, these fragilities are associated with fragility percentage of their constitutive components. For example, a post including n1 transformer, n2 interruption keys, n3 current breakers and n4 current transformers is considered.

Parametric studies show that values of n1, n2, n3 and n4 indicate mean fragility mode and don’t change considerably with change n values (lower than 2%) while their dispersion decreases with decrement of n.

1) minor/slight fragility (ds2)

Minor/slight fragility (ds2) is equal to fragility of 5% of cutoff keys (tilting) or 5% of current breakers (sliding from base or tilting or falling top structure) or slight fragility of control building.

2) Intermediate fragility (ds3)

Intermediate fragility (ds3) is equal to fragility of 40% of cutoff keys or 40% of current breakers or 40% of transformer (such as oil leaking or bushing cracking) or intermediate fragility of control building.

3) extensive fragility (ds4)

Extensive fragility (ds4) is equal to fragility of 70% of cutoff keys or 70% of current breakers or 70% of transformer (such as oil leaking or bushing cracking) or intermediate fragility of control building.

4) complete fragility (ds5)

Complete fragility (ds5) includes fragility of all cutoff keys, current breakers, power transformers and current or building transformers.

For example, data related to 24 posts are considered here that half of them are related to braced equipment. Tables 5 and 6 present mean and dispersion of these data. Figures 18 and 19 show related fragility curves.

d) Experimental fragility curves

Experimental fragility curves have been presented for big earthquakes of the world and compared with analytical curves on the basis of actual fragility and normal gauss distribution.

Table 5-Frgility algorithm of posts (braced-seismic component)

PGA			
Classification	**Fragility mode**	β	**mean acceleration (g)**
Low voltage (ESS1)	slight moderate extensive complete	0.70 0.55 0.45 0.45	0. 15 0.29 0.45 0.90
Moderate voltage (ESS3)	slight moderate extensive complete	0.60 0.50 0.40 0.40	0.15 0.25 0.35 0.70
High voltage (ESS5)	slight moderate extensive complete	0.50 0.45 0.35 0.40	0.11 0.15 0.20 0.47

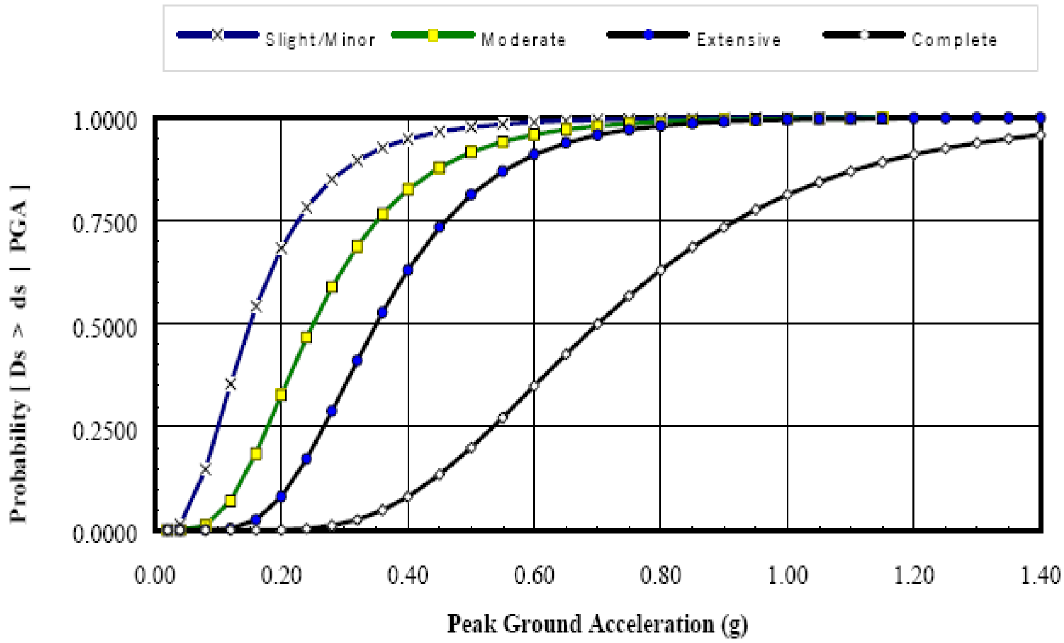


Figure 18-HAZUS fragility curve for moderate voltage post with braced components

Table 6-Frgility algorithm of posts (non-braced-standard component)

PGA			
Classification	**Fragility mode**	β	**mean accleration (g)**
Low voltage (ESS2)	slight moderate extensive complete	0.65 0.50 0.40 0.40	0. 13 0.26 0.34 0.74
Moderate voltage (ESS4)	slight moderate extensive complete	0.60 0.50 0.40 0.40	0.10 0.20 0.30 0.50
High voltage (ESS6)	slight moderate extensive complete	0.50 0.45 0.35 0.35	0.09 0.13 0.17 0.38

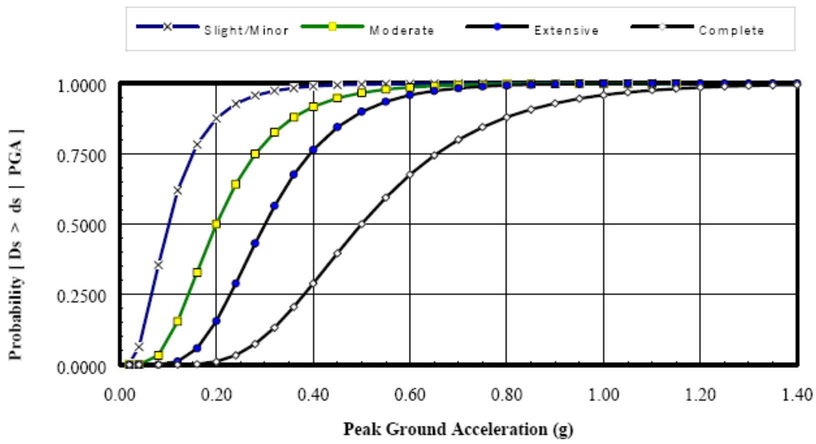


Figure 19-HAZUS fragility curve for moderate voltage post with non-braced components

2-2-3-An example of determination of fragility function for 230.63 kV posts

(1) Transformer model

Two types of 230.63 kV have been modeled with radiator according to figures 20 and 21. Generally, 230.63 kV transformers are modeled according to bushing shape and its geometry. These transformers generally have two types of bushing. The bushing of type 1 involves three porcelain parts and the bushing of type 2 involves a tall porcelain part that is situated over a metallic gasket.

The bushing of type 1 has constant section but the second type involves variable sections which their specifications are presented in table 7. With regard of geometry, there are two power transformers. In the type 1, radiators and oil tank are installed on transformer body. There is no separate base and so there are various types of oil tank shape. Two types of transformer with separate radiator and reservoir are shown in figures 20 and 21 that are connected with transformer.

Main tank has lateral bracing as well as horizontal plate that its dimensions are shown in figure 20. In both types, the base is braced in four angles. Each base involves 6 bolt with diameter 27 and material type of ASTM-A325. Bracing radiators and pipe connection between chamber and radiators in the typewere performed by welding and hardener. In both types, oil tank modeled by shell elements. Transformer was modeled by shell elements and radiator was modeled by three-dimensional elements. Shell elements were used for modeling of transformer tank and mass elements were used for modeling of transformer core and its coil. Bushing was modeled by frame element and connection of shear and axial spring and connections were modeled by types of pipe and beam shaped elements. Gaskets are placed in connection of porcelain and metallic part and above and below of bushing. In bushing of type 1, gaskets are thin plates (figure 20) that are only effective for endurance of little lateral displacement and so aren't modeled in big earthquake displacements. In the type 2 (figure 21) these thick plates (about 5.6 mm) are as a ring of horizontal shape with internal diameter of 250 mm and external diameter of 30 mm that is positioned in two sides of porcelain part.
These continuous components are modeled with parallel separate springs that are located in the peripheral parts of gaskets. Elasticity module of gasket is considered to be 48 MPa according to experimental results of Hergilani in 1999 and elasticity module of porcelains in both types is considered to be 99800 MPa. Table 7, represents other geometrical and mechanical specifications of transformers. As mentioned before, post-tensioned force is not considered. The models were constructed by ANSYS6.1.

Table 7-Structural specifications of transformer

Transformer type	**Type 1**	**Type 2**
dimension of main tank	2.3*7.6*4.1	2.55*7.7*3.9
bushing type	type 1	type 2
total length of bushing	3.775	4.24
porcelain length	1.725	3.6
number of the section specifications	26	16
support type	constant	constant
radiator type	separate	connected
thickness of upper plate of main tank	12	20
dimension of main tank hardener	Box 0.2*0.1*.004	Plate0.2*.02
elastic module of aluminum core	71000	71000
elastic module of insulator	99800	99800
elastic module of gasket	---	---
lower diameter of porcelain	26	26
porcelain thickness	3	3
diameter of aluminum core	30.5	30.5

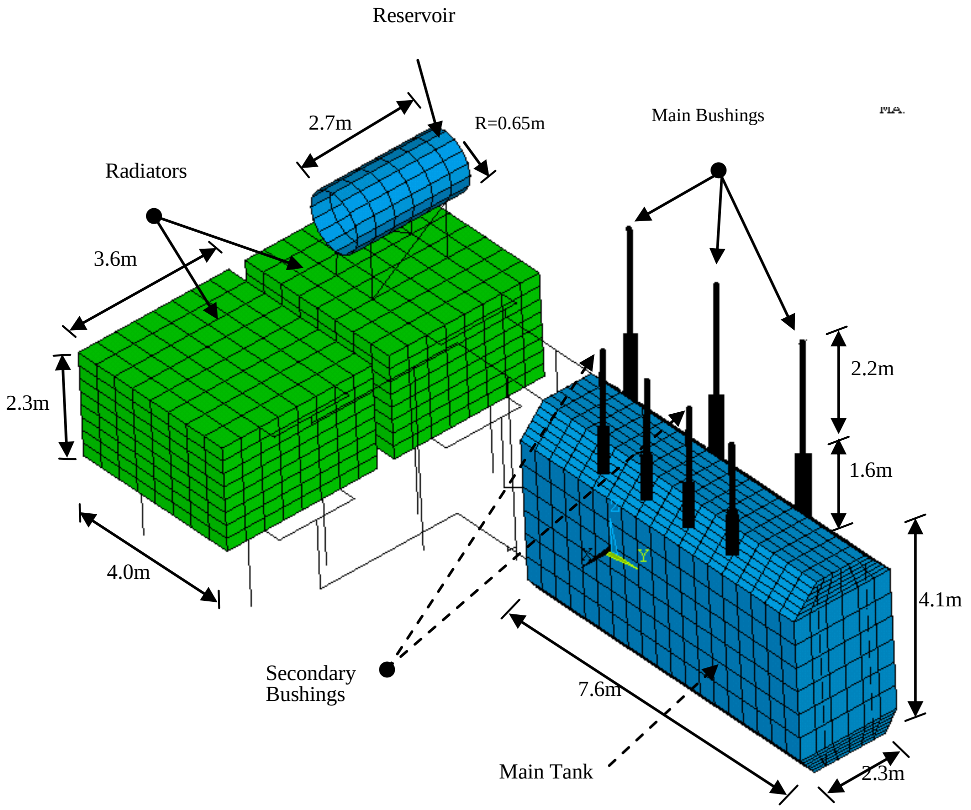


Figure 20-Three-dimensional finite element model of type 1 transformer

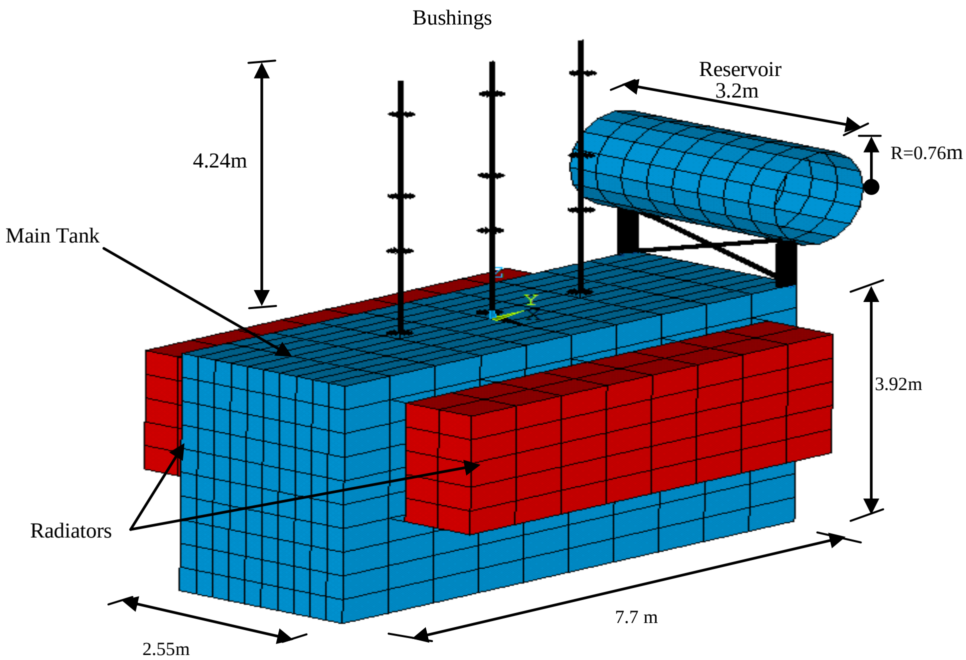


Figure 21-Three-dimensional finite element model of type 2 transformer

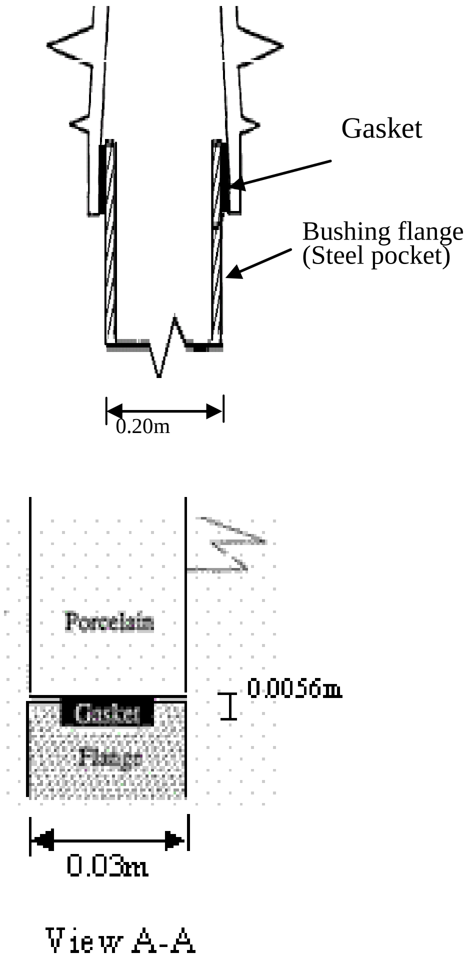


Figure 22-Details of gasket connection in type 1 bushing

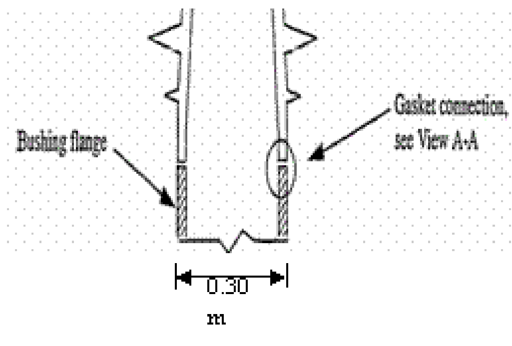


Figure 23-Details of gasket connection in type 2 bushing

(2) Modal analysis

Modal analysis is performed to calculate natural frequencies. Tables 8 and 9 present 10 first frequencies of both types of transformer and bushing. Various geometrical and structural specifications in bushing and main tank lead to considerable variation of natural frequencies in both types of transformer. Primary modes of transformer response are as shift of main tank in the direction of lower hardness.

First and second modes of type 1 transformer in Y direction are associated with frequency of 0.424 and 0.558 Hz respectively. In mode 1, main bushing and in mode2, secondary bushing are affected from solid movement. Natural mode of separate bushing is bending mode with frequency of 43.382 Hz. Frequency of the second and third transmission modes in Y direction are 1.942 and 2.03 Hz respectively. In the first and second mode, bushing is affected and rotates solidly. The first natural mode of separate bushing is bending with frequency of 5.090 Hz which is shown in figures 24 to 30.

Table 8-Natural frequency of whole transformer system in Hz

Mode No	Mode No.1	Mode No.2	Mode No.3	Mode No.4	Mode No.5	Mode No.6	Mode No.7	Mode No.8	Mode No.9	Mode No.10
Type 1	0.425	0.558	0.713	0.722	0.760	0.907	0.924	1.087	1.494	1.693
Type 2	0.475	1.942	2.004	2.089	2.676	2.706	2.733	3.065	4.702	5.121

Table 9-Natural frequency of separate transformer system in Hz

Mode No	Mode No.1	Mode No.2	Mode No.3	Mode No.4	Mode No.5	Mode No.6	Mode No.7	Mode No.8	Mode No.9	Mode No.10
Type 1	43.382	43.382	70.829	70.829	137.51	177.68	211.06	211.06	401.92	493.27
Type 2	5.090	5.090	29.212	29.212	29.289	29.289	79.156	94.597	94.597	127.92

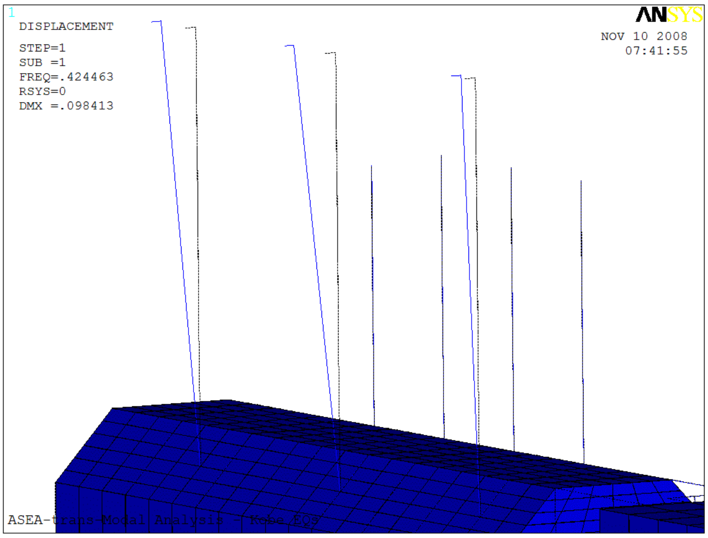


Figure 24-Mode no.1 in type 1transformer as shift of tank in the direction of Y with frequency of 0.42 Hz

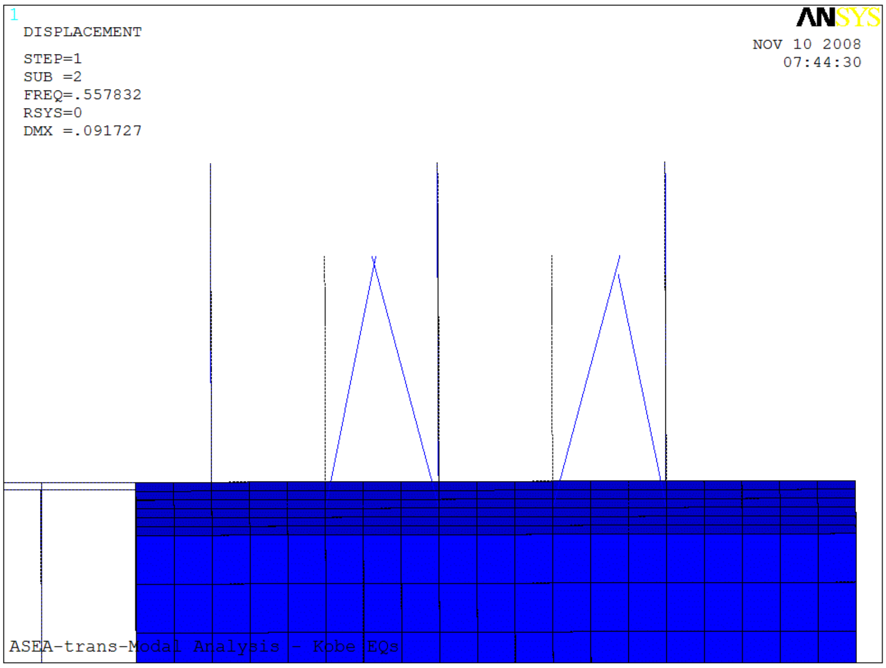


Figure 25-Mode no.2 in type 1transformer as shift of tank in the direction of Y with frequency of 0.56 Hz

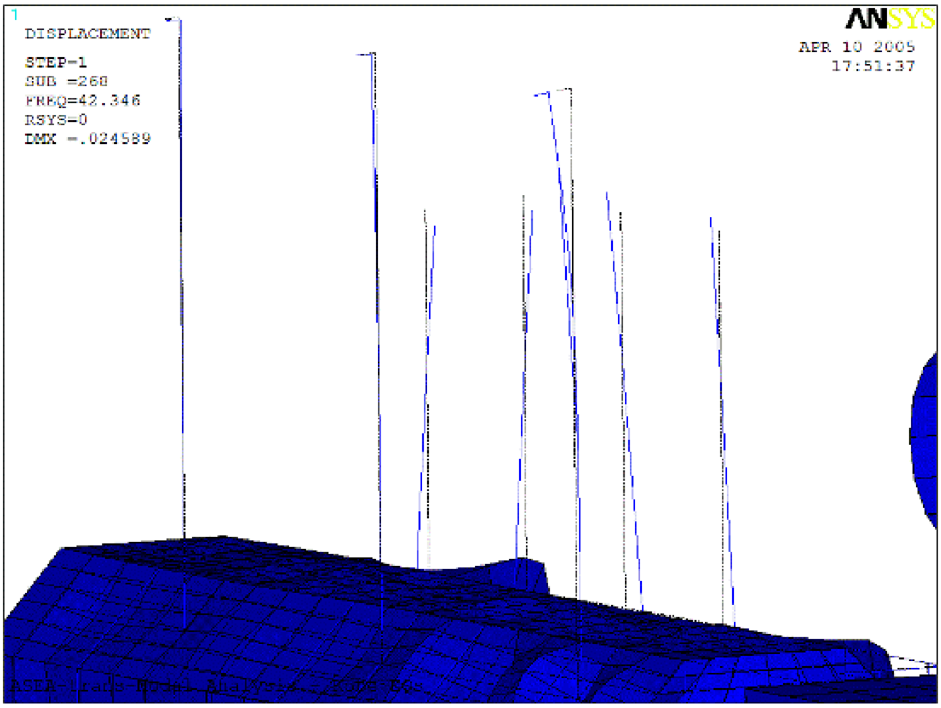


Figure 26-Mode 268 in type 1as bending of main bushing in the direction of Y with frequency of 42.57 Hz

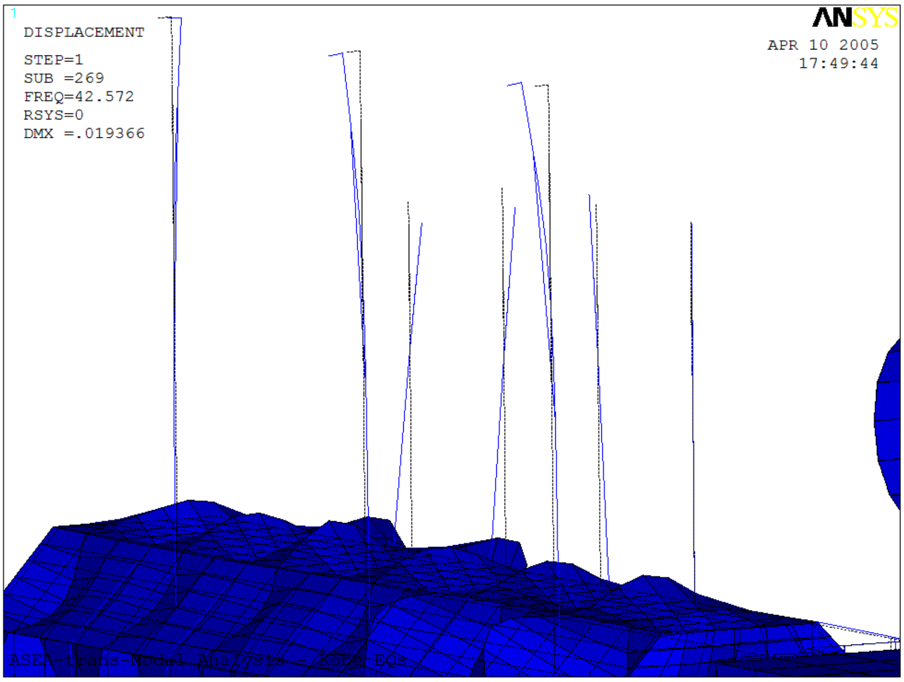


Figure 27-Mode 269 in type 1as bending of main bushing in the direction of Y with frequency of 42.57 Hz

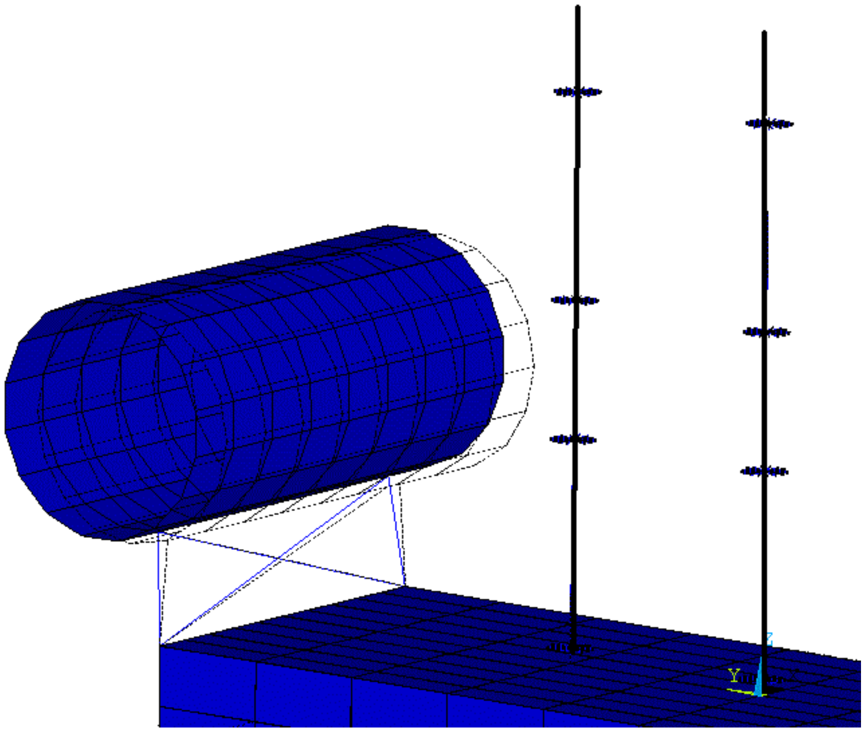


Figure 28-Mode 1 in type 2as shift in the direction of Y of oil tank with frequency of 0.47 Hz

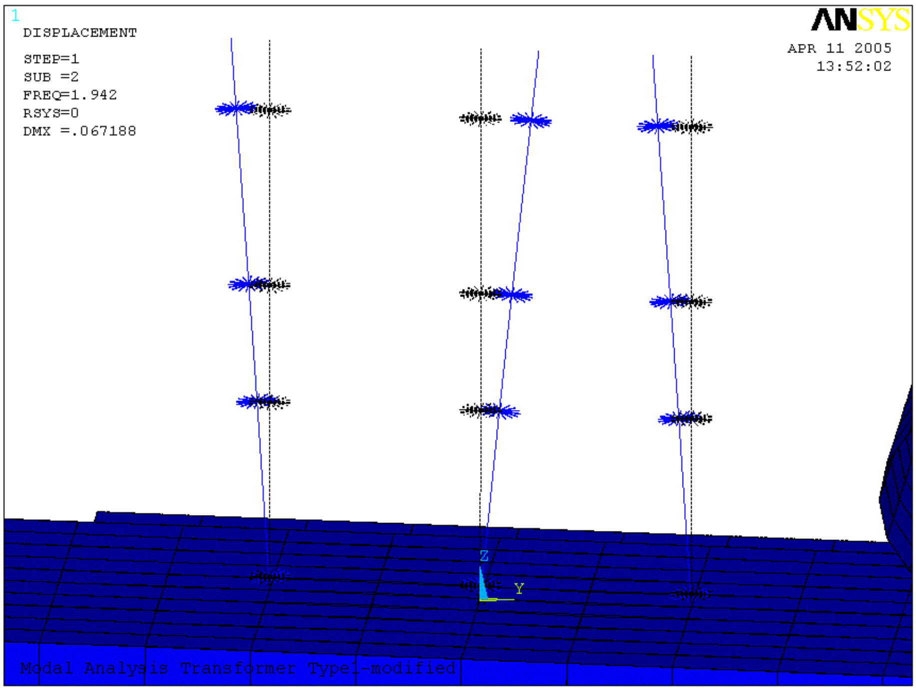


Figure 29-Mode 2 in type 2as shift in the direction of Y of oil tank with frequency of 1.94 Hz

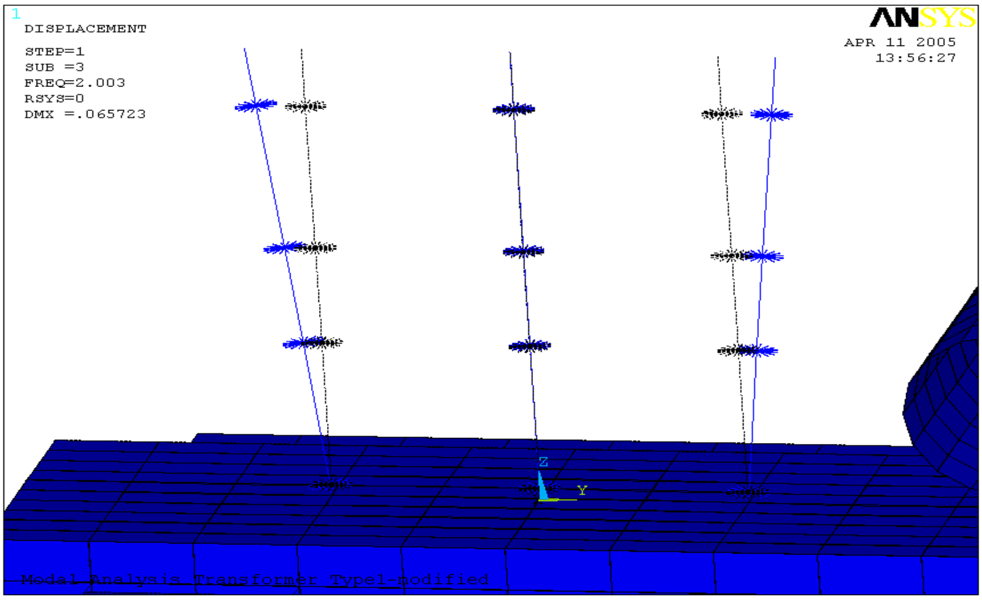


Figure 29-Mode 3 in type 2as shift in the direction of Y of main tank with frequency of 2.73 Hz

(3) Time history analysis

Figure 31 shows lateral displacements in various levels of bushing in type 1 transformer. Figure 32 shows lateral displacements in type 2 transformer as well. Bushings in type 1 transformer in the direction of y show more displacements about 0.807 meters than to the direction of x. Since bushing specification is the same in both directions, amplification of displacement in one direction against another direction is due to difference in transformer specifications. In type 2, displacement in the direction of x is always lower than y direction because of more frequencies in x direction. Displacement in the direction of x in type 1 bushing is lower than type 2. Figure 33 shows relative displacement in x direction among top, below and middle of type 1 bushing and figure 34 shows displacement related to y direction of type 2 bushing. Relative displacement of initial and end of bushing is very important to reach it fragility. As shown in following figures, relative displacement of initial and end of type 1 bushing in x direction is 28 mm and lower than displacement in y direction, i.e. 36 mm. However, in y direction, displacement of type 1 is 807 mm due to amplification that is much more than corresponding value of type 2, namely 69 mm.

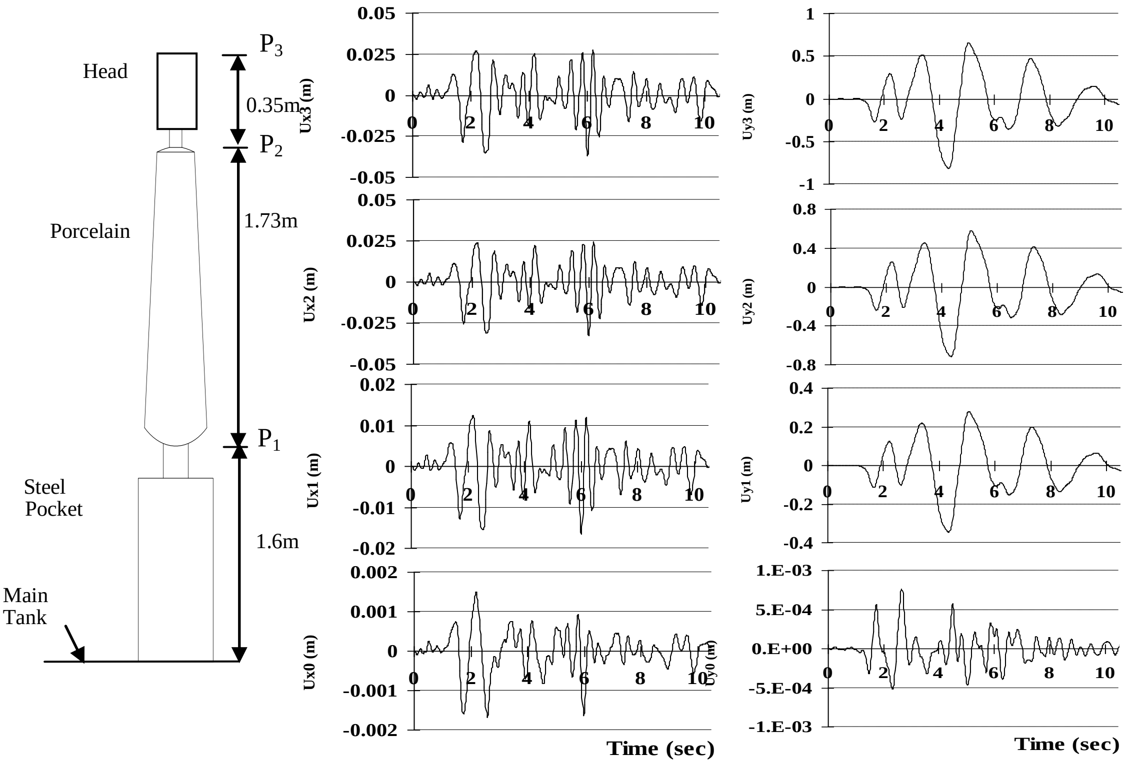


Figure 31-Relative displacement of various levels of bushing of type 1 transformer

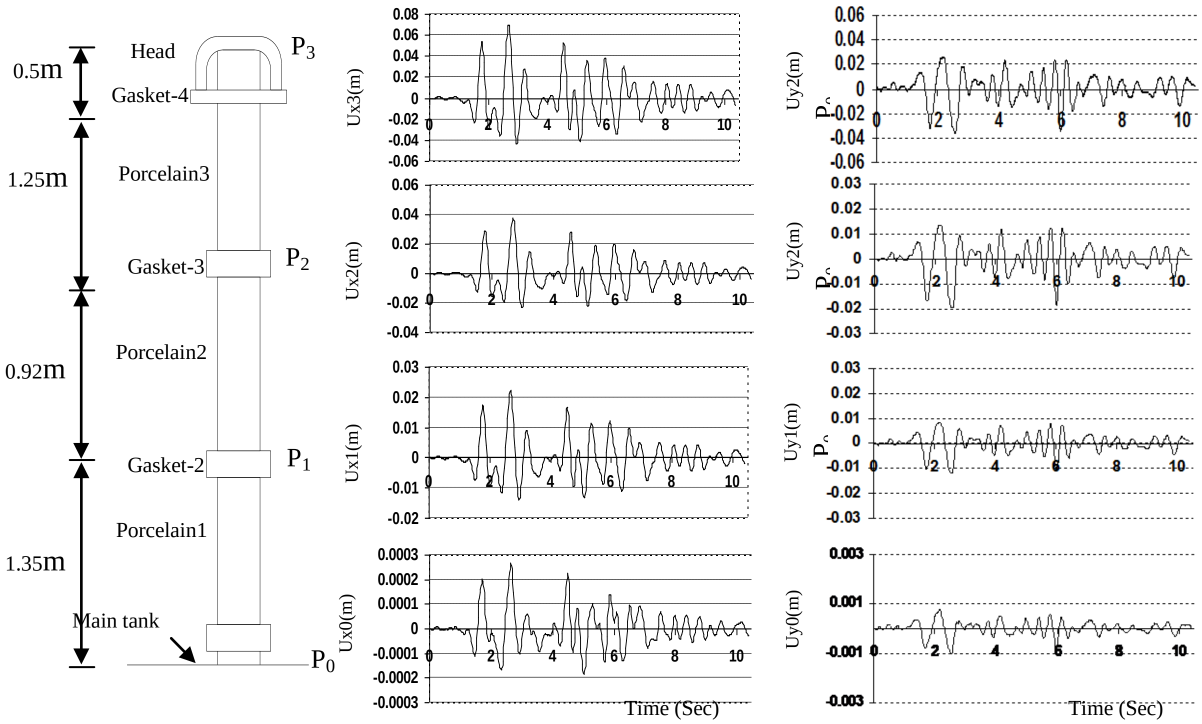


Figure 32 -Relative displacement of various levels of bushing of type 2 transformer

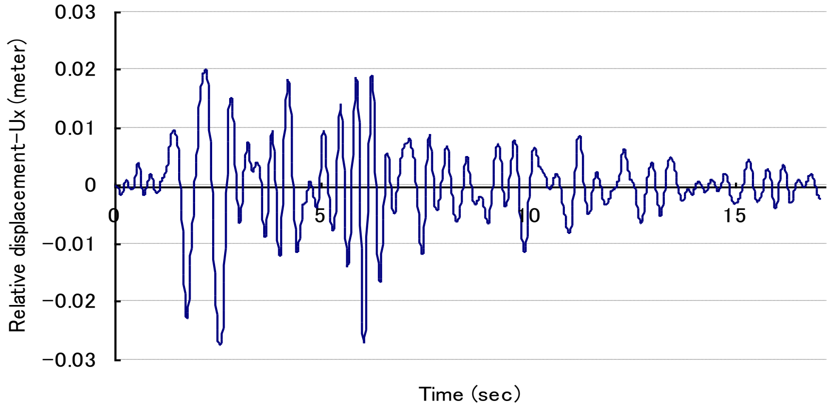


Figure 33-Displacement Ux in the initial and end of type 1 bushing

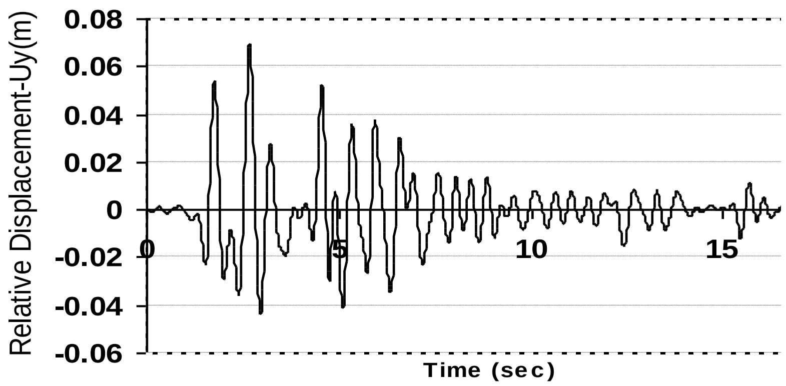


Figure 34-Displacement Ux in the initial and end of type 2 bushing

(4) Interaction of transformer and bushing

As told before, there are considerable differences between test results and actual observations of pervious earthquakes mainly due to interaction of transformer-bushing. Here, interaction effect is investigated through examining bushing model separately from transformer. In the previous section, difference between vibration period of individual bushing and whole transformer was examined. Dynamic analysis of time history was performed on separate bushing with condition of pervious problem.

Vertical displacement over transformer tank in the bushing base is a very effective parameter in seismic design of bushing that lead to flexibility of behaviour. Vertical displacements of bushing base for type 1 and 2 transformer are shown in figures 35 and 36, respectively.

Figure 37 show slight displacements U_x and U_y and magnification in various levels of independent bushing. Maximum lateral U_x and U_y are 9.7 mm and 12.9 mm respectively, while these parameters in middle bushing of transformer and on above of it are 37.2 mm and 8.7 mm respectively. Drastic discrepancy is visible in other levels between displacements of individual bushing and whole system. Displacements in two directions are differed slightly in individual bushing but in whole system there is high difference between them. Structural specifications of bushing are same in horizontal plan but in whole system, bushing is intensified only in y direction. This phenomenon isn't observed in individual bushing.

Figure 38 show low magnification of lateral displacements U_x and U_y in cap level of type 2 individual bushing with 0.16 mm and 0.21 mm respectively, while, in whole system, same values in middle bushing are 36.4 mm and 69 mm respectively. Generally, transformer interaction effect on bushing appears to be very considerable with comparison of displacements of two systems.

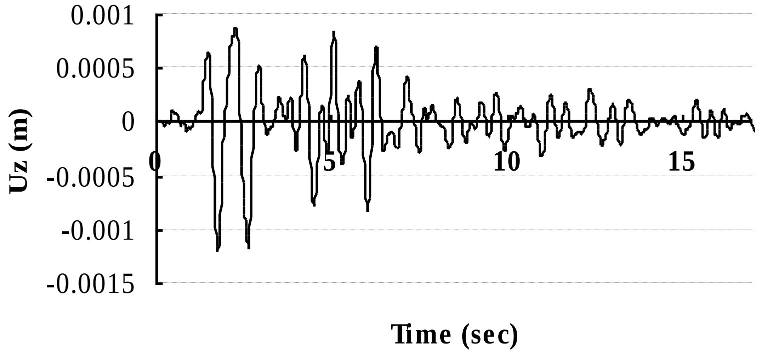


Figure 35-Vertical displacement over transformer tank on the base of middle bushing in type 1 transformer

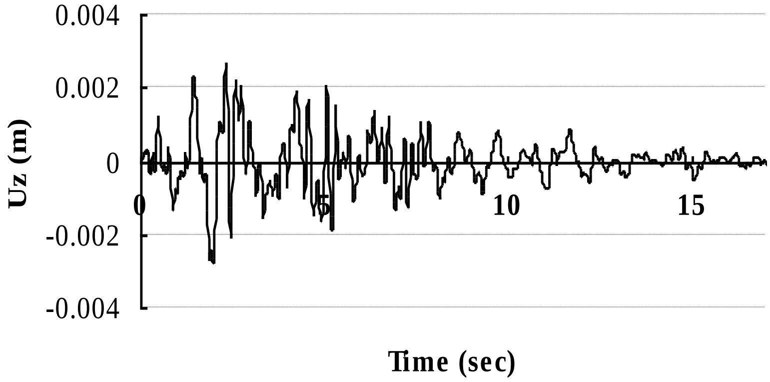


Figure 36-Vertical displacement over transformer tank on the base of middle bushing in type 2 transformer

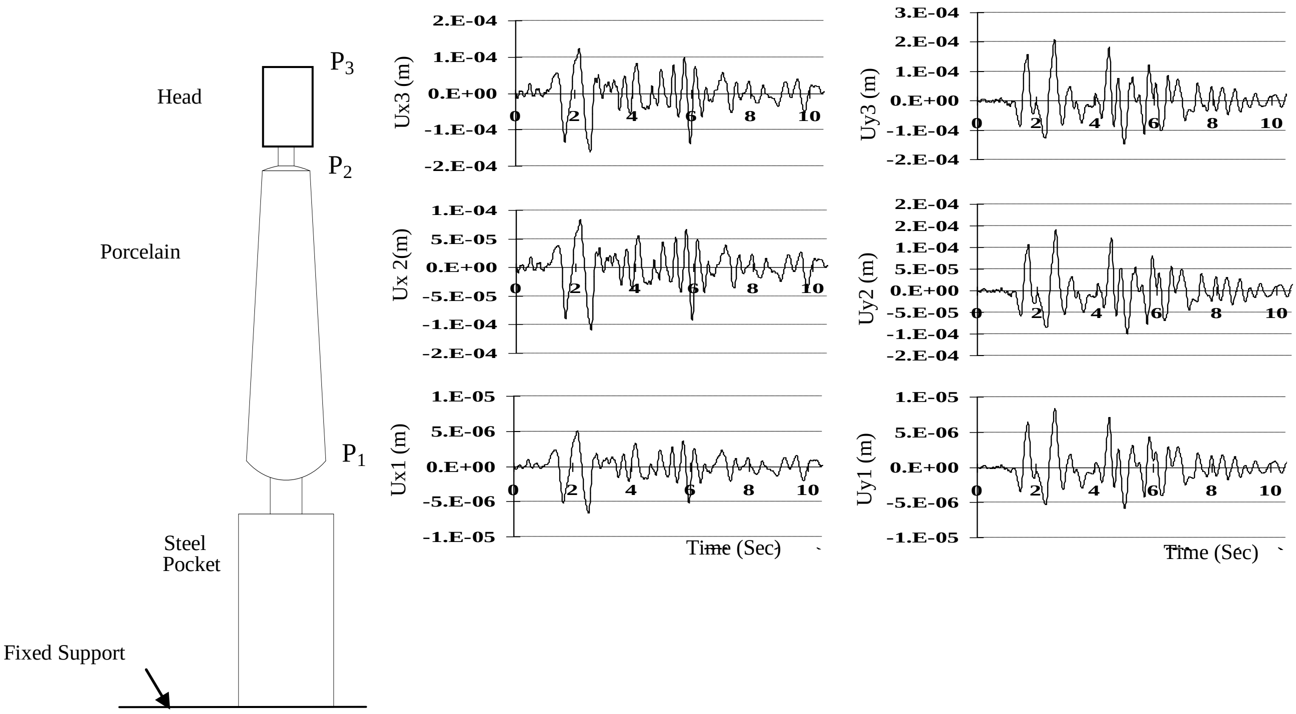


Figure 37-Lateral displacements U_x and U_y of various levels of individual bushing type 1

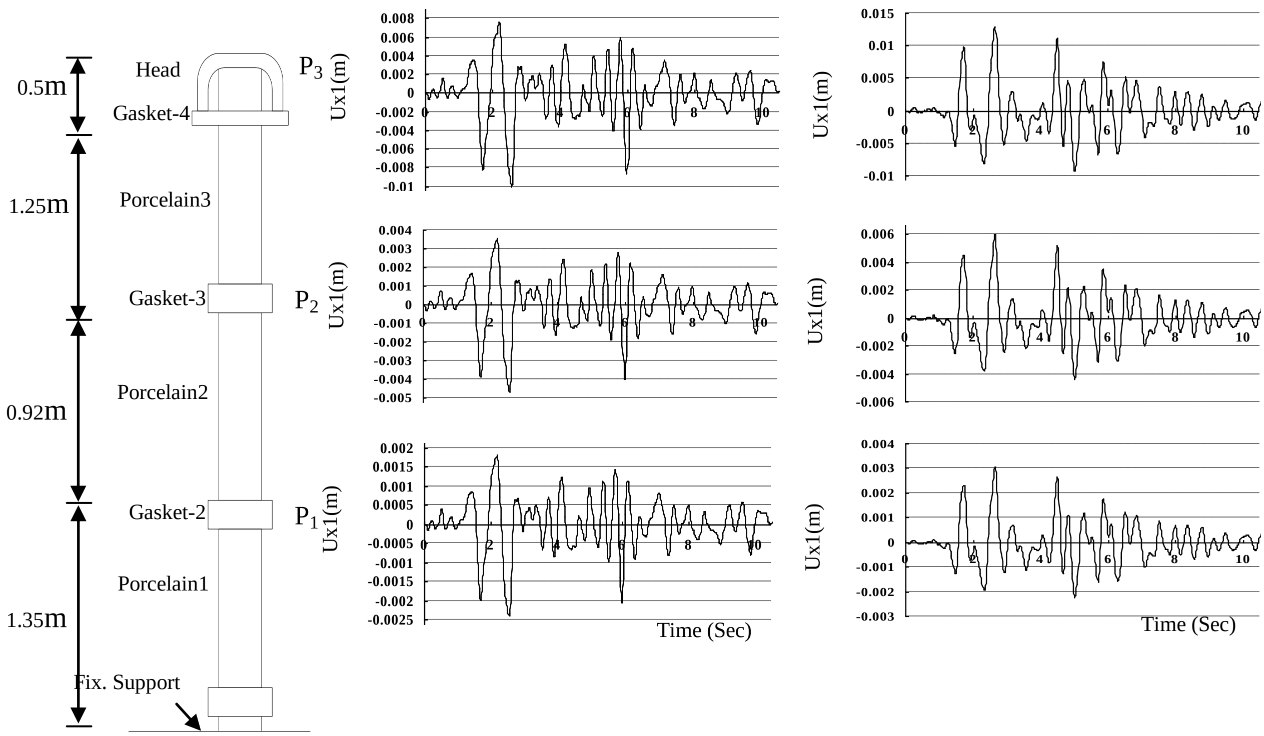


Figure 38-Lateral displacements U_x and U_y of various levels of individual bushing type 2

(5) Fragility function

Fragility function for major, intermediate and slight fragility is obtained using three-dimensional linear dynamic analysis under selected earthquake for both types of transformer.

Normal distribution is selected for calculation of mean and standard deviation depends on fragility situation of system. In this distribution, variation factor is assumed to be 0.2. Fragility function for type 1 was obtained on the basis of response value in x direction of the transformer that hadn't been intensified.

a) minor fragility

In state of minor fragility for type 1, fragility is assumed as uplift connection between steel pocket and end of porcelain part of bushings that lead to oil leaking. Uplift is occurred due to vertical displacement in rotation of solid body. Vertical displacements are negligible in comparison with uplift, so bushing solid motion is considered as criterion of this fragility and defined as relative solid displacement between two ends of bushing porcelain. Relative displacement of two ends of bushing that lead to oil leaking in type 1 is 10.35 mm and in type 2 which is assumed for above porcelain is equal to 6.75 mm. Uplift of connection is computed as following:

$$\frac{\text{Uplift}}{\text{Porcelain design}} = \frac{\text{Lateral relative displacement}}{\text{Porcelain length}}$$

According to laboratory results, mean allowable value o uplift in connection for type 1 is considered to be 1.2 mm. Accelerations related to mean and standard deviations are 0.302g and 0.0605 g respectively. For type 2, the same criterion exists with mean and standard deviation of 0.238g and 0.047g. Concept of extracting fragility function together with allowable criterion of uplift displacement and response curve of type 1 and type 2 are illustrated in figures 39 and 40. Fragility function is defined as accumulative distribution function of normal distribution curve. Figures 41 and 42 show fragility curve related to minor damage for both type of transformers.

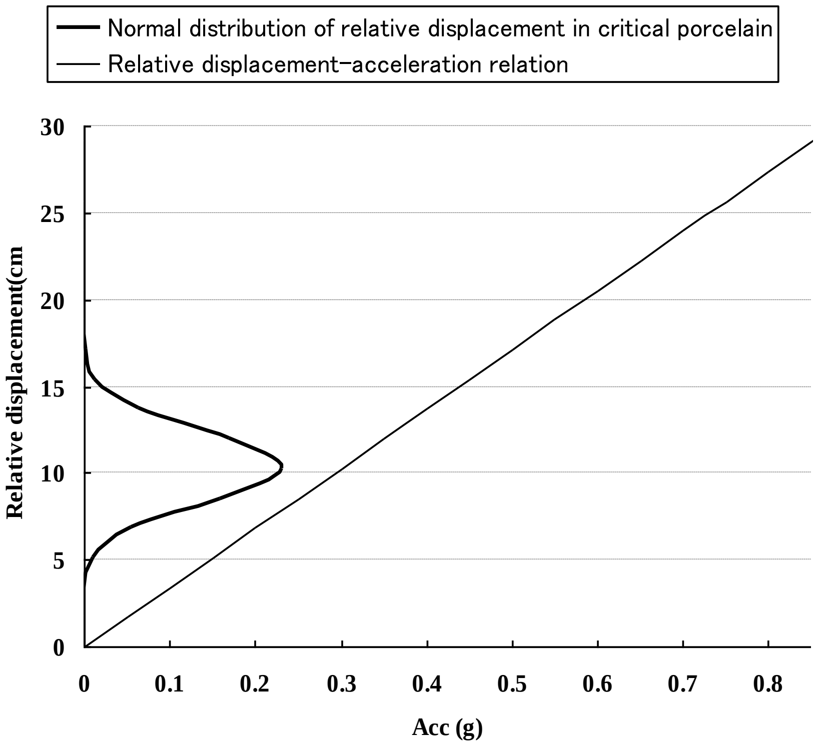


Figure 39-Concept of normal distribution of relative displacement in porcelain in fragility mode type 1

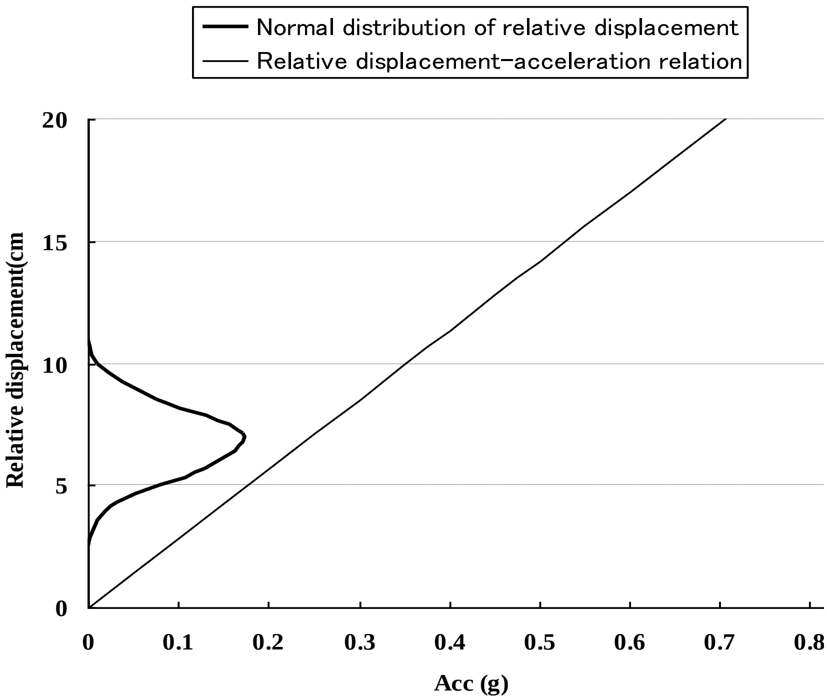


Figure 39-Concept of normal distribution of relative displacement in porcelain in minor fragility mode type 2

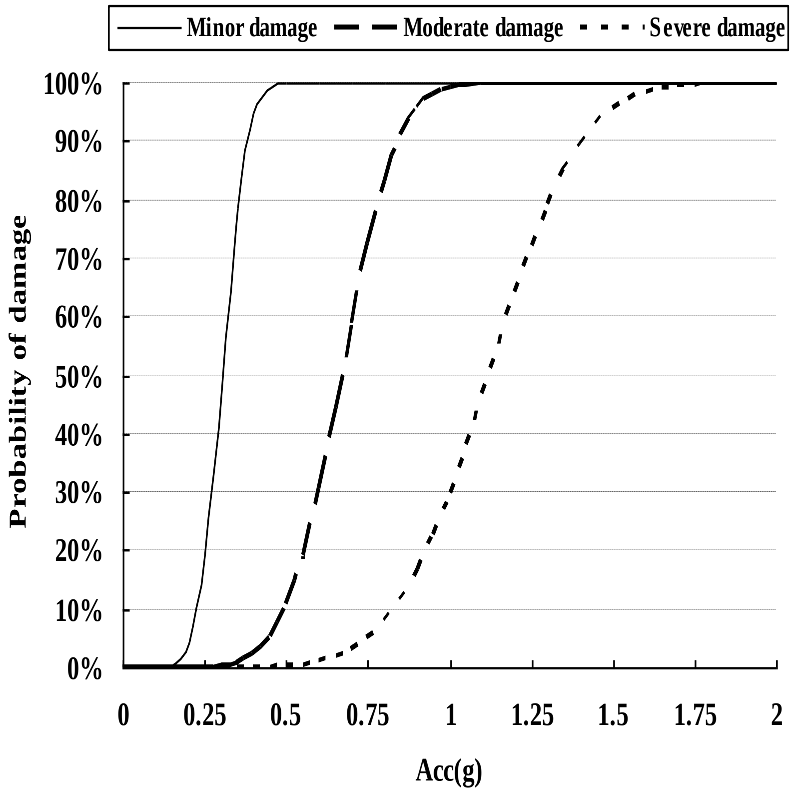


Figure 41-Fragility curve related to minor damage for transformer type 1

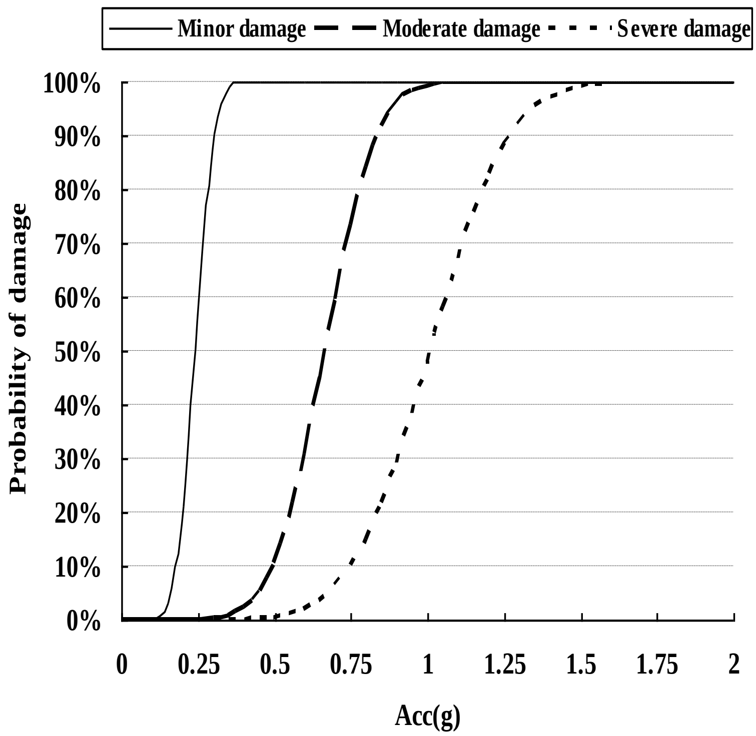


Figure 41-Fragility curve related to minor damage for transformer type 2

b) Moderate fragility

Moderate fragility is defined as porcelain fracture in main bushing due to bending. Depends on connection type of porcelain connection and metallic gasket, critical mode of stress concentration exist between ends of porcelain and metallic gasket of type 1 according to figure 22. Fragility criterion for smaller lateral displacement in type 2 is bending as well but for higher displacements, stress concentration occur between porcelain and metallic flange according to figure 23. In both types, fragility occurs due to more displacement and stress concentration in connection with porcelain so it is defined as fragility criterion for medium damage mode.

Contact surface in both type of transformer is considered to be 3% of total surface of burden removing. Maximum stress is obtained on the basis of maximum bending moment in connection. Allowable mean stress in porcelain is assumed to be equal to 31.55 MPa. Maximum concentration of response stress in contact surface of porcelain end and metallic gasket in type 1 is equal to 38.07 MPa. According to corresponding acceleration associated to allowable moderate stress of 31.55 MPa and standard deviation of 0.063 MPa are equal to 0.668g and 0.133g, respectively. In type 1, maximum stress concentration between end of porcelain end and metallic flange is 35 MPa. Mean and standard deviation values of acceleration for allowable stress of 31.55 MPa are 0.737g and 0.147g, respectively, according to figure 43. Fragility function of mean damage is considered to be similar to minor damage mode as accumulative distribution function of normal distribution curve. Figures 42 and 43 shows fragility curves of mean damage state for both types of transformers.

Figure 43-Concept of normal distribution of tensile stress in porcelain for moderate fragility mode in transformer type 1

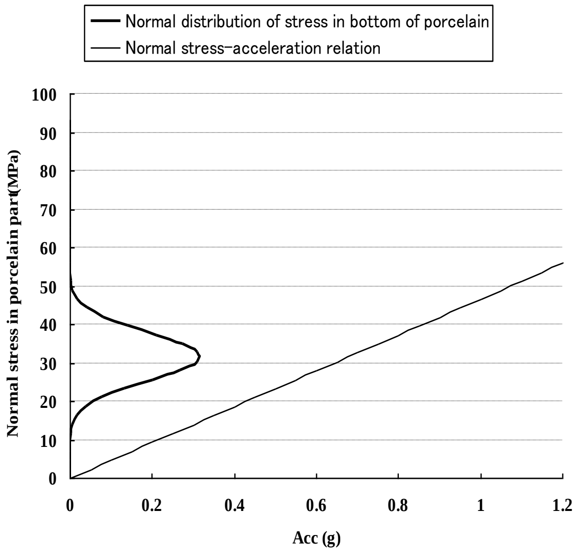


Figure 44-Concept of normal distribution of tensile stress in porcelain for moderate fragility mode in transformer type 2

c) Severe damage

Severe damage of transformer is defined as bracing fragility in the base of the main tank of transformer. The main tank in any types of transformer has four bases in edges and each one involve six bolt with diameter of 27 mm. Bolt material is according ASTM-A325. Bolt capacity is controlled on the basis of shear and extension. Shear yield in both types leads to severe damage. According to Iranian standard of designing steel structure, maximum allowable shear stress for this type is 145 MPa. Maximum response of horizontal force in the most critical transformer support type 1 is 363.59 kN that cause shear stress of 105.9 MPa. In type 2, maximum horizontal force is 403.9 kN and maximum shear stress is 117.5 MPa. Mean and standard deviation of acceleration for allowable shear stress of 145MPa is 1.119g and 0.224 g for type 1, according to figure 45, respectively and 1.01g and 0.202g for type 2, according to figure 46. Fragility function of severe damage mode is defined similar to other mode as accumulative distribution function of time distribution curve. Fragility curves of severe damage mode for both types of transformers are shown in figures 45 and 46.

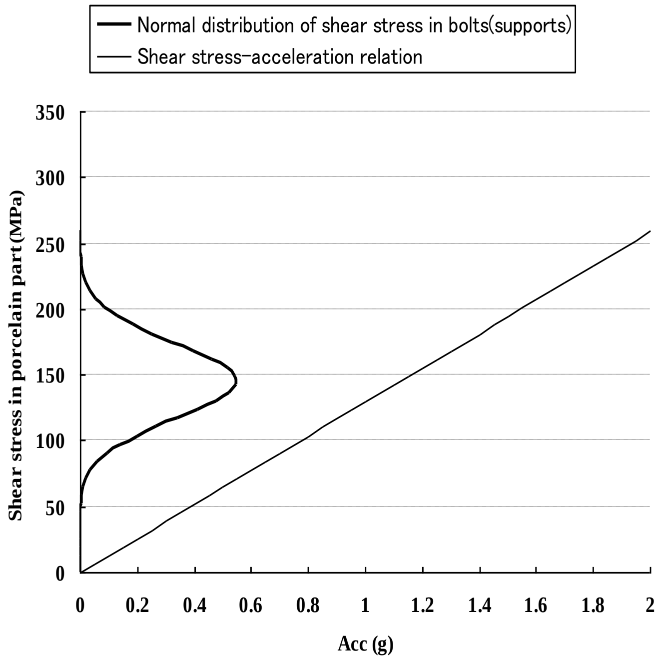


Figure 45-Concept of time distribution of shear stress in bracing bolt of transformer support type 1 in sever fragility mode

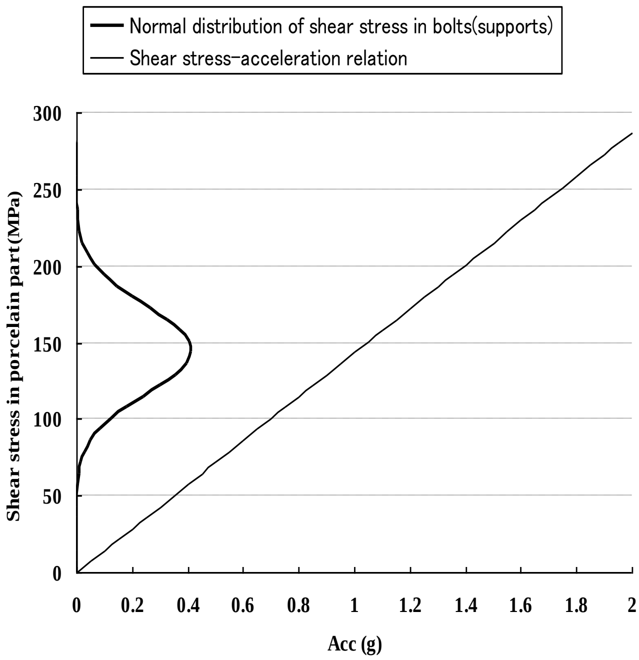


Figure 45-Concept of time distribution of shear stress in bracing bolt of transformer support type 2 in sever fragility mode

Transformer show better strength for oil leaking as minor fragility of type 2. In type 2, porcelains are separated with horizontal gasket and porcelain length is shorter than type 1. As a result, lateral relative displacement, which is considered as criterion of oil leaking, is smaller. For moderate fragility mode, thin gasket in bushing of type 1 leads to direct contact of porcelain and metallic cover in comparison to type 2 that involve thicker gasket. More length of bushing in type 2 causes more moment, as well. In total, both types have similar strength for this level of damage. Type 1 shows better strength for severe fragility mode, because connection of radiators and oil pipes is fixed. Another reason is lower mass of type 1 than type 2.

(6) Comparison with other fragility curves

Two comparisons were carried out with following research results:

- Technical guideline of HAZUS99 that presents fragility curves of 230kV posts.
- Technical guideline of UWG that presents fragility curves of 230kV transformers.

Figures 47 to 49, represent comparisons of minor, moderate and severe damages, respectively.

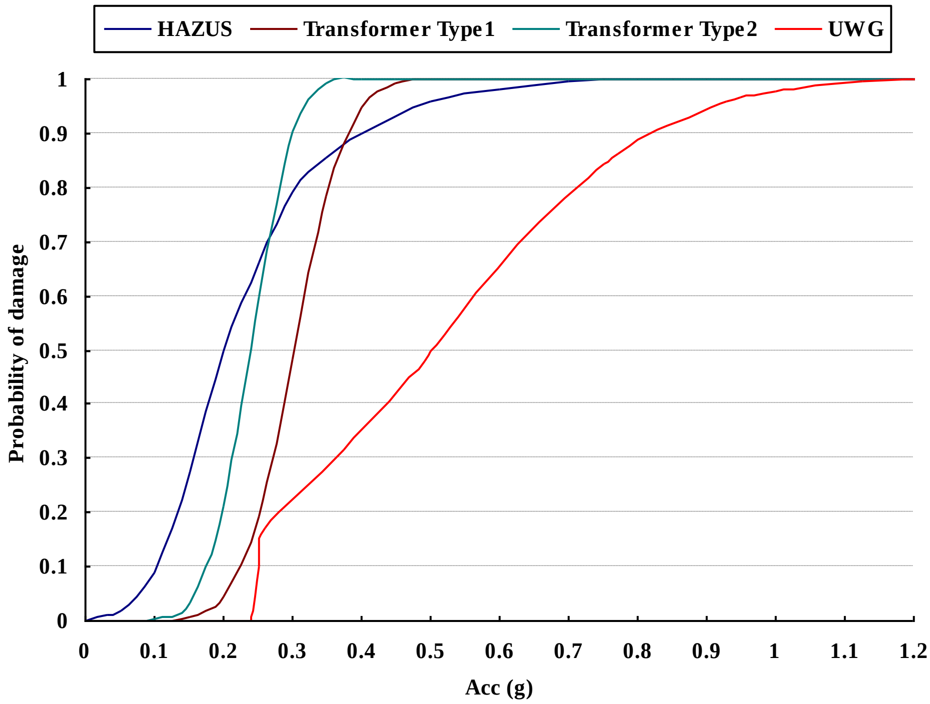


Figure 47-Comparison of fragility curves of transformers for minor fragility mode

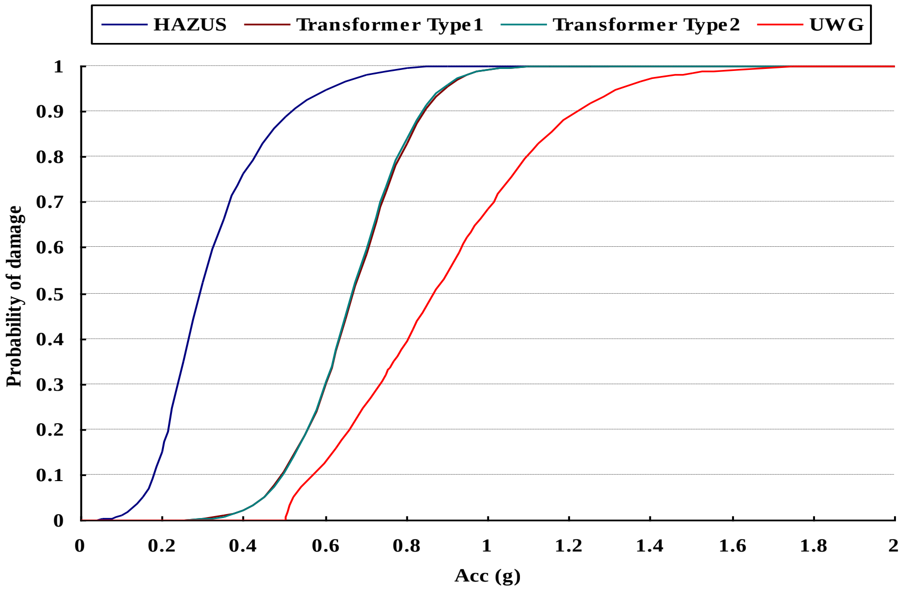


Figure 48-Comparison of fragility curves of transformers for moderate fragility mode

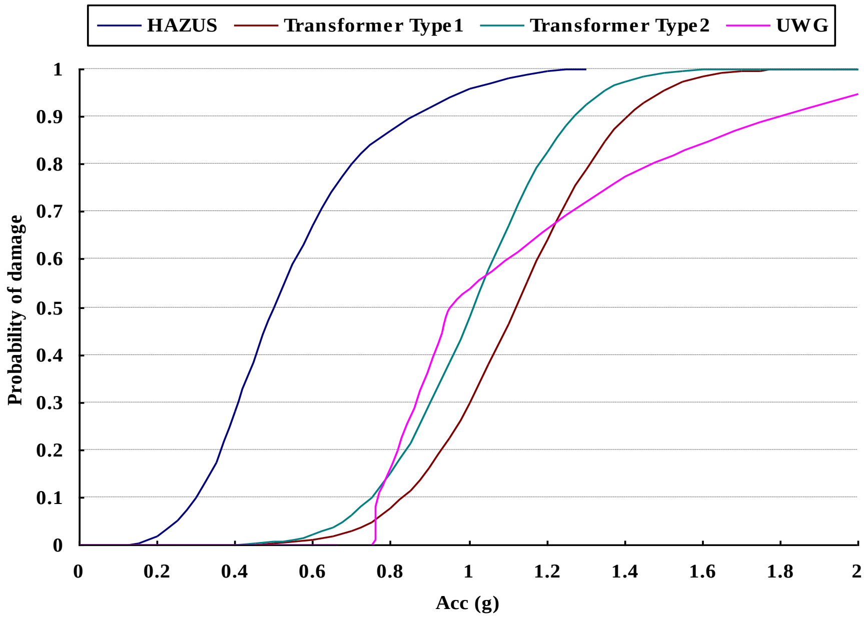


Figure 49-Comparison of fragility curves of transformers for severe fragility mode

(7) Conclusion

1-Flexibility of transformer top plate affect considerably on dynamic specifications of bushing and sometimes cause resonance

2-Flexibility of transformer top plate decrease natural frequency of bushing.

3-Bushings are the most vulnerable member of transformer, because they displace considerably in earthquake.

4-Connection type of porcelain, metallic part and details of gasket connection are important factors in bushing vulnerability.

2-2-4-Method of determination of fragility function for 63.20kV

a) Modelling post based on shape

b) Member vulnerability curves

1) General assumption of model

-63.20kV transformer

According to available data in tables 10 and 11, it is assumed that oil volume is about 6000 to 7000 litre and its total weight is 30 ton. Transformer capacity is 5000 to 20000 KVA and capacity of 30 ton transformer is about 10000 KVA.

Table 10-63.20 kV transformer data

Power transformer:
Voltage: 63 / 20Kv
Manufactored by : Delle- Alsthom-1967
Total weight: 31500 Kg
Oil weight: 6500 Kg
Core & winding weight: 19500 Kg

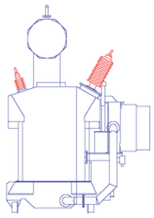


Table 11-Weight and dimension of 1000KVA transformer

Manufacturer	weight	dimension width×height×depth
Toshiba	26tonf	3.4m x 3.3m x 3.4m
Nissin Electric	29.5tonf	4.9m x 3.2m x 3.4m

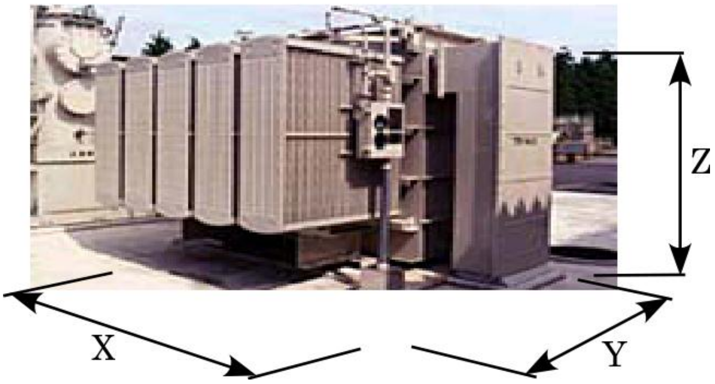


Figure 50-Transformer shape

According to data of table 11, model dimension and weight are as following

Dimension: 3.4m×3.3m× 4.2m

Weight : 28ton

Two models are considered for connection of body to foundation which one of them is considered with bracing bar and another is considered with wheel on rail. Figure 51 shows position of bracings and wheels.

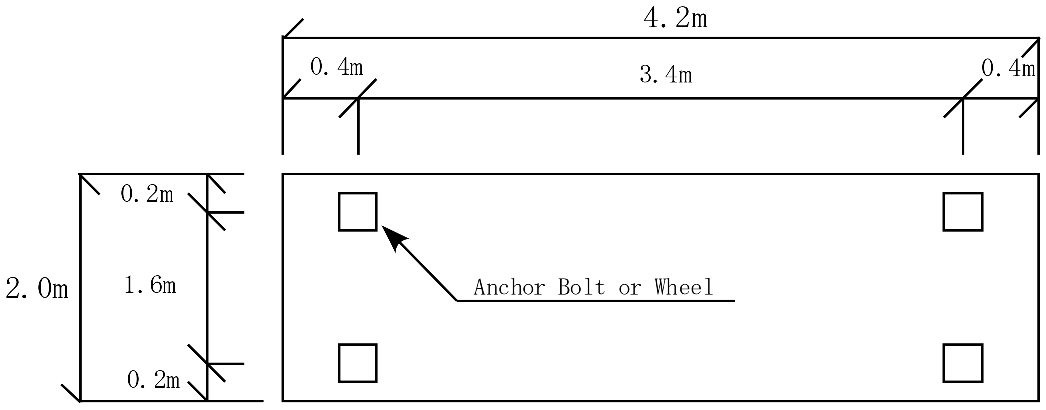


Figure 50- Position of bracings and wheels

Table 12 presents weight of each part.

Table 12-Weight of different parts

main body	**24.92 ton**
tank	2.8 ton
bushing	5.19 ton
total (including oil)	32.9 ton

-Bushing and tank

Connection of accessory parts such as bushing and oil tank is considered as figure 52. Position of bracings and wheels are shown in figure 52. Dimension of these part are shown in figure 53.

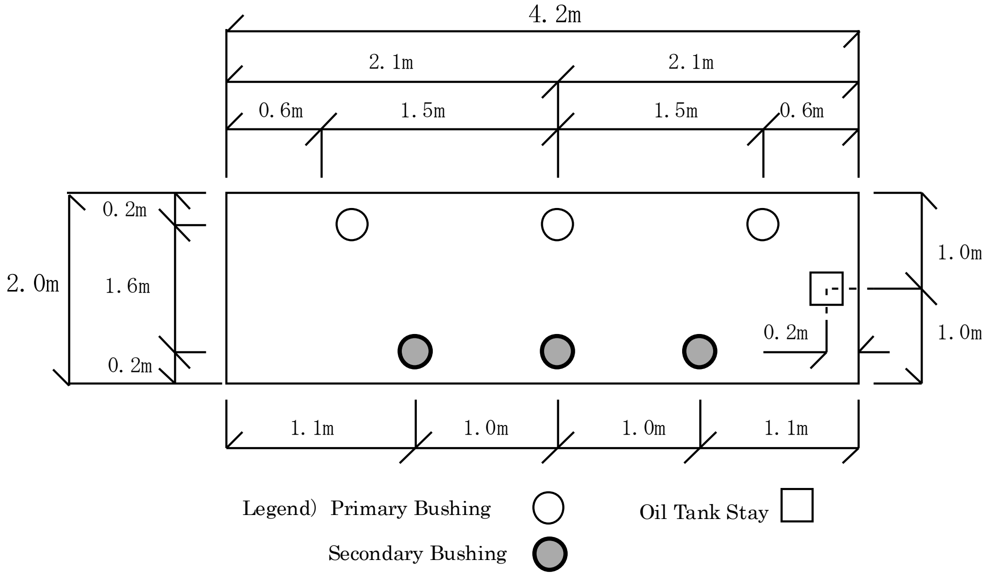


Figure 52- Position of bracings and wheels

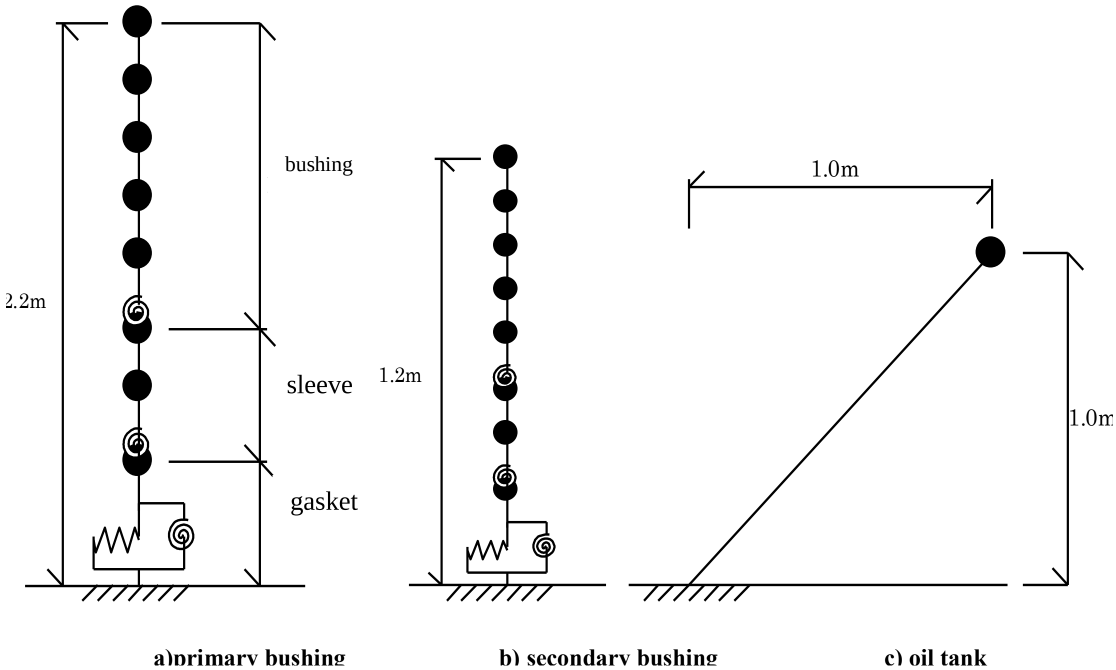


Figure 53-Lateral view of accessory parts

2) Analysis of braced transformer with bracing bar

Figure 54 shows analytical model of transformer.

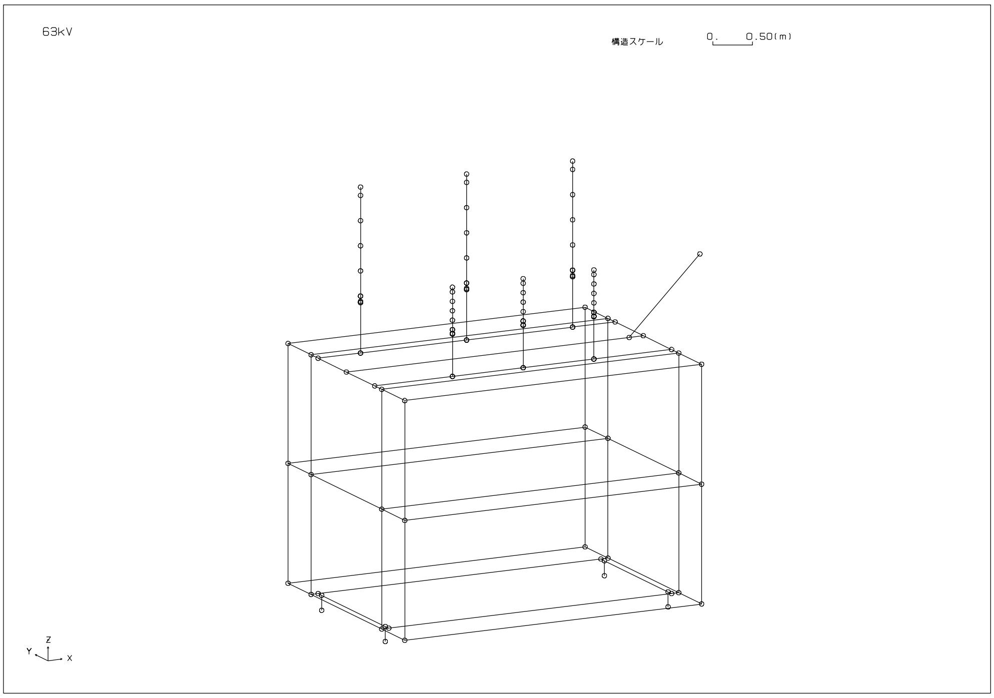


Figure 54-Analytical model of 63.20 kV transformers

According to preliminary investigations, height of primary bushing is lower than 2m in Iran; however its structural and material characteristics weren't available so bushings with 20 and

70 percent of Japanese 500kV bushing height were considered for analysis. Weight and springy percent were considered to be equal to 20% and 10% of Japanese bushing respectively. Main body was modelled with linear beam element and concentrated wheels were placed in various elements.

-Bushing characteristics

Applied bushing characteristics are presented in tables 13 and 14. Figure 55 shows arrays of primary and secondary bushing.

Some analysis results are shown in figure 56. Oil tank vibrate with frequency lower than 10 Hz in the first. Primary bushing vibrates with frequency up to 14 Hz from the second to seventh mode. Secondary bushing vibrates up to frequency of 28 Hz from the eighth mode. Generally, bushings have frequency of more than 10 Hz so occurrence of resonance in them during earthquake is impossible.

-Fragility mode

Shear rupture of bracing bars is defined as predominant fragility mode of transformer and oil leaking from bushing end is defined as minor fragility mode.

3) Results regarding to braced transformer with bracing bar

-Predominant fragility mode

Each of four transformer base endures 8 tone weight of transformer. It is assumed that transformer is designed on the basis of 30% seismic intensity and each base has 4 bracing bar, namely each bracing bar is designed for 600 kg shear force. It is assumed that 12M bracing bar with allowable stress of 980 kg permanent load is used.

-In Japan, allowable shear and tensile stress for provisional load is 1.5 times of permanent load.

If this discrepancy from vibration is related to 25 allowable stresses of provisional load, variation factor is equal to:

$$1 \times \frac{1}{5/1} \times 0/5 = 0/165$$

Table 13-Element specification of bushing beam

(1) Primary bushing

element	materials	cross section square meter	length meter	inertia (m4) Ix=Iy	Elastic module (t/m2)	Poisson ratio	damping ratio
Beam1	Steel	2.38E-02	0.674	2.43E-03	2.1E+07	0.3	0.05
Beam2	Steel	5.73E-01	0.016	5.62E-02	2.1E+07	0.3	0.05
Beam3	Steel	4.95E-03	0.07	7.61E-05	2.1E+07	0.3	0.05
Beam4	Porcelain	5.34E-02	0.336	1.64E-03	7.4E+06	0.3	0.05
Beam5	Porcelain	4.56E-02	0.34	1.07E-03	7.4E+06	0.3	0.05
Beam6	Porcelain	3.82E-02	0.332	6.58E-04	7.4E+06	0.3	0.05
Beam7	Porcelain	3.08E-02	0.336	3.79E-04	7.4E+06	0.3	0.05
Beam8	Steel	3.43E-03	0.112	1.02E-04	2.1E+07	0.3	0.05

(2) Secondary bushing

element	materials	cross section square meter	length meter	inertia (m4) Ix=Iy	Elastic module (t/m2)	Poisson ratio	damping ratio
Beam1	Steel	1.55E-02	0.566	6.65E-04	2.1E+07	0.3	0.05
Beam2	Steel	3.68E-01	0.008	1.38E-02	2.1E+07	0.3	0.05
Beam3	Steel	2.61E-03	0.05	1.09E-05	2.1E+07	0.3	0.05
Beam4	Porcelain	2.14E-02	0.126	1.72E-04	7.4E+06	0.3	0.05
Beam5	Porcelain	1.71E-02	0.126	1.04E-04	7.4E+06	0.3	0.05
Beam6	Porcelain	1.32E-02	0.126	5.79E-05	7.4E+06	0.3	0.05
Beam7	Porcelain	9.75E-03	0.126	2.91E-05	7.4E+06	0.3	0.05
Beam8	Steel	1.69E-03	0.062	1.97E-05	2.1E+07	0.3	0.05

Table 14-Element specifications of bushing spring

	element	method	location	spring ratio	damping ratio
primary	Spring 1	translation	Bottom of Pocket	9800	0.05
	Spring 2	rotation	Bottom of Pocket	130340	0.05
	Spring 3	rotation	Bottom of sleeve	25990	0.05
	Spring 4	rotation	Bottom of porcelain	294	0.05
secondary	Spring 1	translation	Bottom of Pocket	5096	0.02
	Spring 2	rotation	Bottom of Pocket	686	0.02
	Spring 3	rotation	Bottom of sleeve	490	0.02
	Spring 4	rotation	Bottom of porcelain	640	0.02

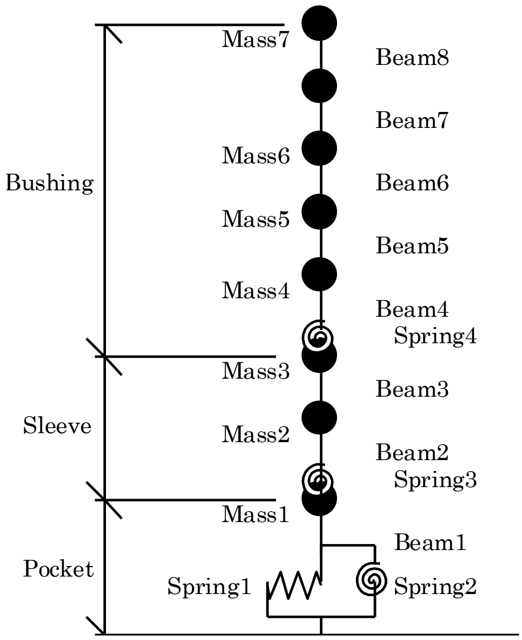


Figure 55-Analytic model of bushing

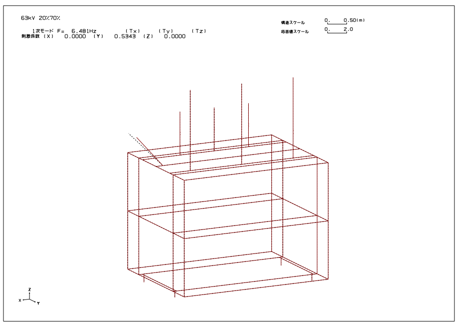
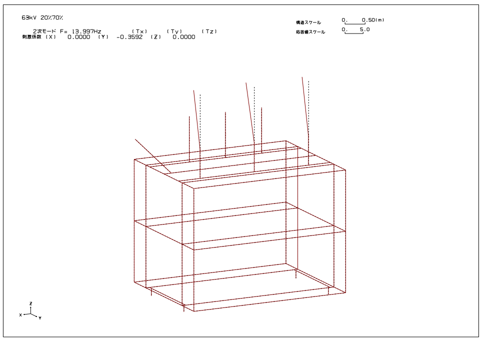
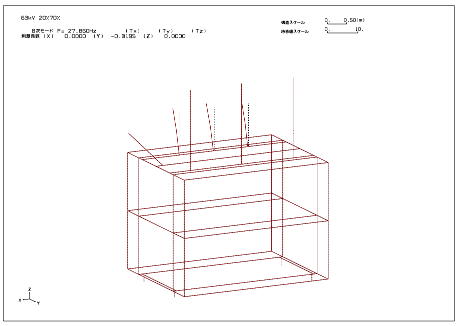
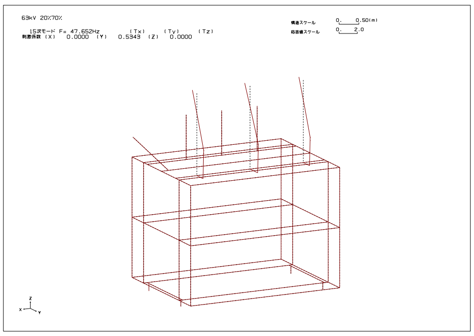
	
a) first mode	**b)second mode**
	
c)eighth mode	**d) fifteenth mode**

Figure 56-Deformational mode of transformer

Fragility curve associated with shear fracture is shown in figure 57 in which shear force involve time distribution with variation factor of 0.3 and allowable value is equal to above-mentioned number. For instance, figure 57 shows comparison of fragility curves of complete rupture mode of low voltage post based on HAZVS99 that one of them is related to seismic design. Obtained fragility curve based on shear rupture of bracing bar is similar to HAZVS99 curves, but without seismic design. However, it must be noticed that these fragility curves are related to whole post, not a transformer.

When acceleration of 500gal is applied in shorter direction, namely y direction, resultant reaction is equal to 4.54 ton shear and 3.04 ton tensile force. So, for acceleration of 500gal, tensile force is lower than half of weight, therefore, tensile fragility mode occurs rarely. In some posts, transformers only has radiator in one direction. In these cases, radiator that consists about 40% of the total weight is analysed according to figure 58. In this case, tensile force is unequal in two directions but in the case of input acceleration of 500gal is lower than transformer weight.

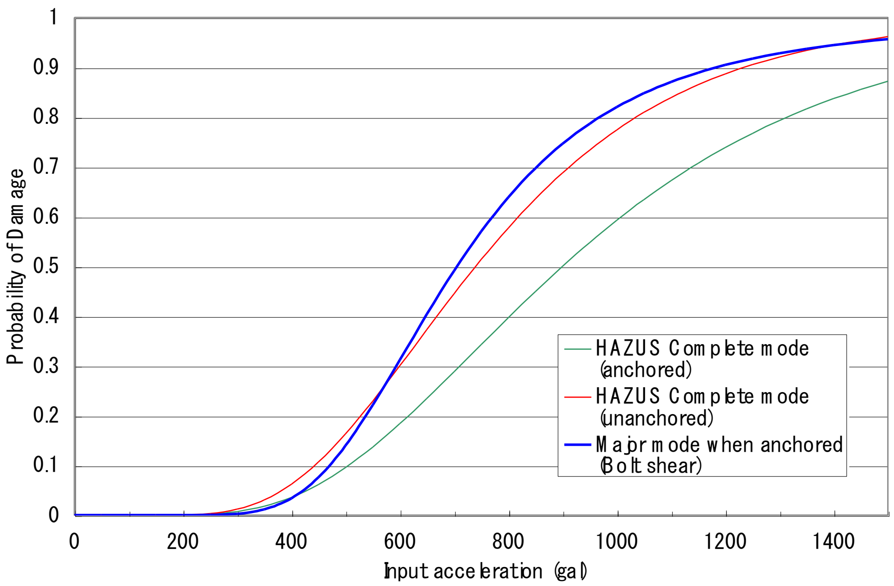


Figure 57-Transformer fragility curve in predominant fragility mode

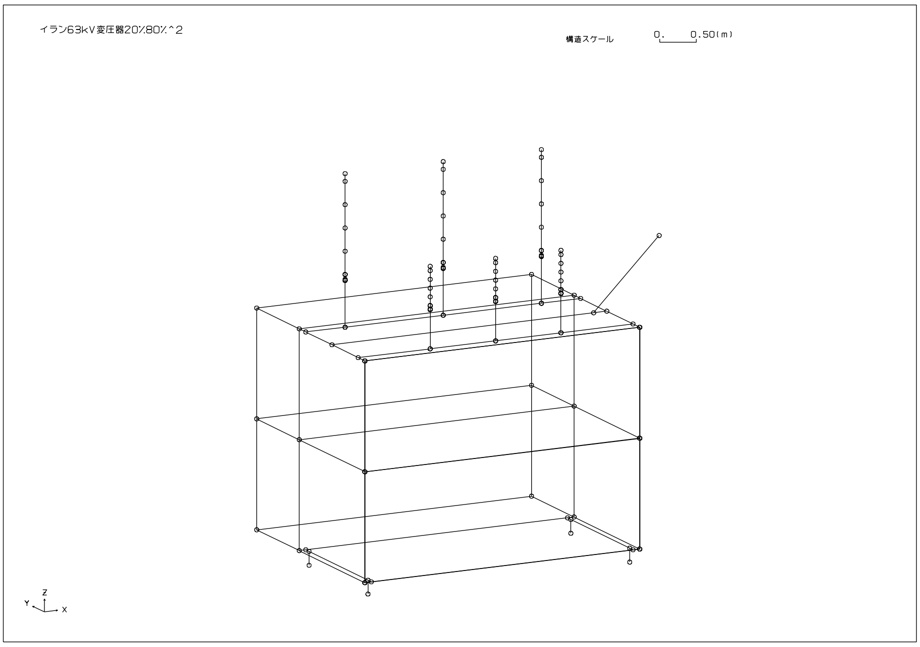


Figure 58-Transformer model with radiator in one side

-Minor fragility mode

Minor fragility is assumed as cracking in the end of bushing and oil leaking that occurs as 0.01 degree of spring element. In this case, fragility curve has variation function of 0.2 as figure 59.

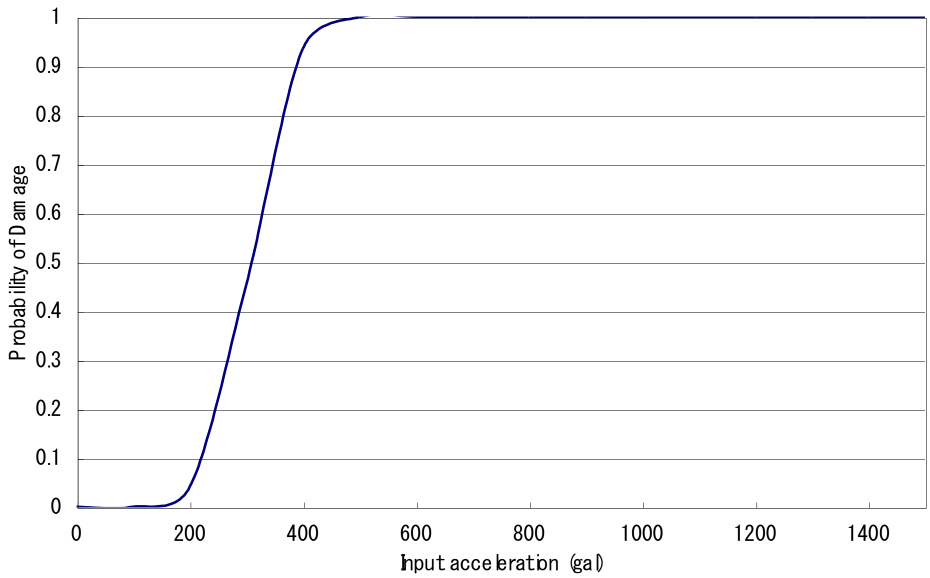


Figure 59-Fragility curve of transformer in minor fragility mode

4) Analysis of transformer situated on wheel

In this section, transformer situated on wheel is analysed in which, main body is positioned on four wheels that is located on two rails. Part of a wheel situated on rail is modelled as a node spring against horizontal motion. Direction of input acceleration is assumed to be in the direction of rail. If rail surface is smooth and rectangle, ground horizontal movement isn't translated to transformer in rail direction. But in presence of friction, transformer moves as well. In this case, transformer displacement must be absorbed by bushing. If this displacement is higher than allowable value of bushing, it causes major fragility. Figure 60 show position of spring elements in which rotational freedom degrees are locked.

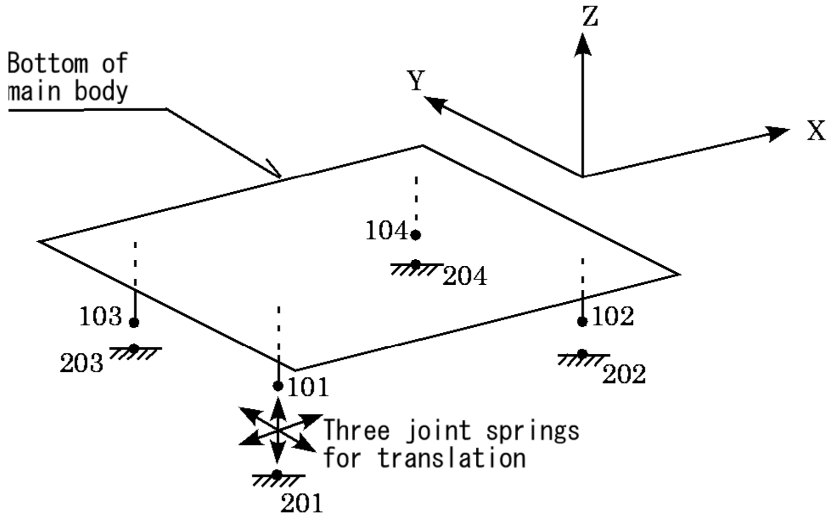
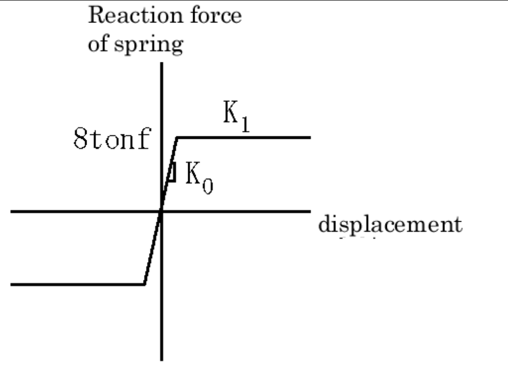


Figure 60-Position of node springs in the wheel position of transformer

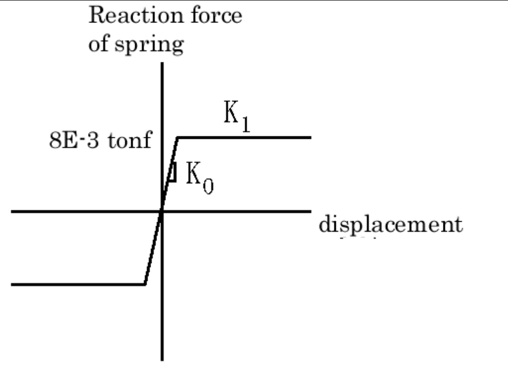
Figure 61 shows specifications of connecting element that are presented as nonlinear elastic. Total weight is equal to 32 ton then each wheel receives 8 ton force. In the perpendicular direction to rail it is assumed that connecting elements become plastic in acceleration of 1g, namely transformer is putted out of rail according to figure 61. Primary hardness k_0 is assumed to be 1e5 that show plastic solidity specification. Similar to behaviour in the direction of rail, wheel motion is initiated by force of 8e-3 with assumption of friction factor of 0.001. In vertical direction, when tensile force is equal to weight, spring become plastic. In the bottom direction, spring shows linear behaviour with sufficient hardness of k_0.

According to figure 67, in a transformer with above-mentioned specifications, three sine waves are produced in nodes of 201 to 204 in ground level that have frequencies of 1Hz and 2 Hz. Maximum corresponding amplitude are 500 gal, 300 gal and 100 gal respectively.

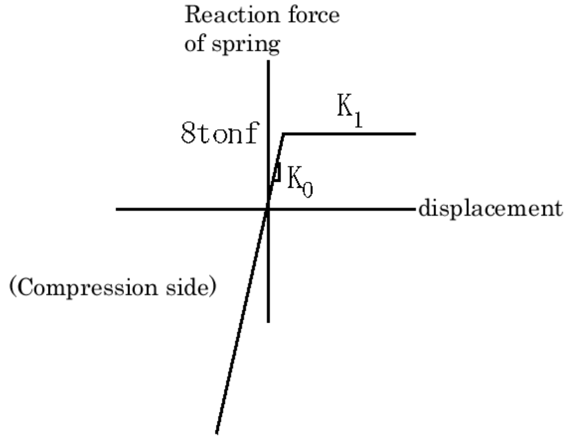
Spring ratios k1 in plastic range or rotation mode of wheel are 0.1 t/m, 1t.m, 10t/m and 100t/m. Figure 62 shows relation between springy and maximum displacement based on input amplitude parameter. Figure 63 shows relation between input acceleration and maximum displacement based on parameter of springy ratio.



X direction perpendicular to rail

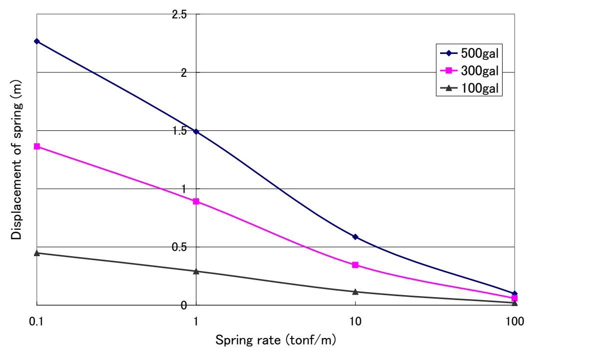


Y direction perpendicular to rail

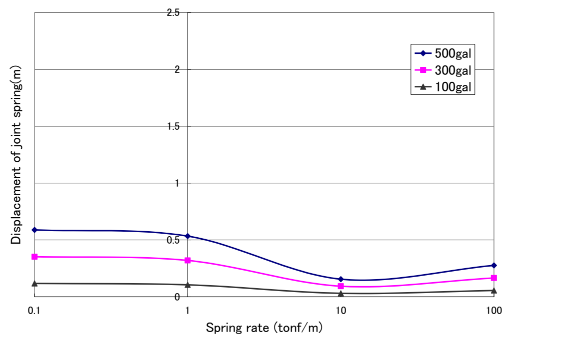


vertical z direction

Figure 61-Specifications of connecting element

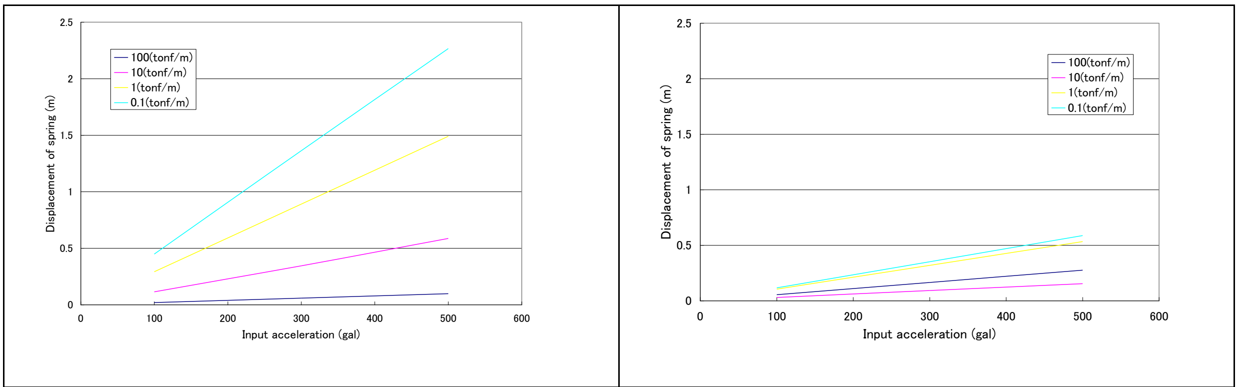


(1) 1Hz input



(2) 2Hz input

Figure 62 -relation between springy and maximum displacement based on input amplitude parameter



(1) 1Hz input	(2) 2Hz input

Figure 63-Relation between input acceleration and maximum displacement

The smaller springy ratio, the higher maximum displacement in input frequency of 1 Hz, based on figure 63. In the input frequency of 2Hz, maximum spring is converged to smaller value of displacement of input frequency of 1Hz without regarding springy ratio.

Figure 63 indicates that maximum displacement is more affected from input frequency that from vibration amplitude. If it is assumed that allowable displacement of bushing transformer and its connected wires to be 50 cm then major fragility never occur in input frequency of more than 2Hz. However, with increment of input frequency, this frequency become nearer to the natural bushing frequency and bushing fragility probability is increased.

During change of ground movement direction, direction of wheel movement is changed with special phase difference that some changing friction occurs from rotational friction to sliding friction means that direction of body movement changes with higher friction force.

In order to modelling this phenomenon, specification of spring in figure 61 is considered as two-linear with kinematic hardening.

Figure 64 show an example of displacement time history. Transformer body show permanent vibration after ending ground movement. In practice, body will have some permanent displacement depends on potential energy and friction. Figure 65 shows relation between springy ratio and maximum displacement in terms of input parameter of amplitude. Figure 66 shows relation between input amplitude and maximum displacement in terms of springy ratio parameter. Figure 67 show one sample of displacement force history.

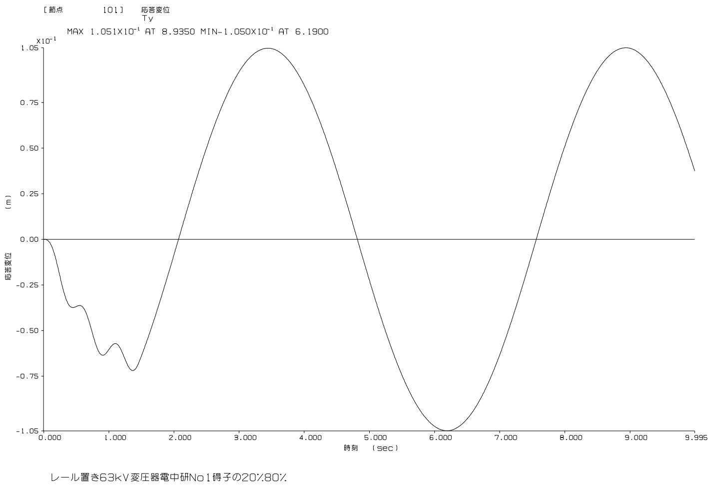
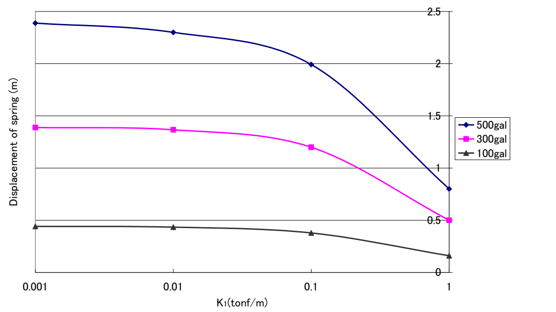
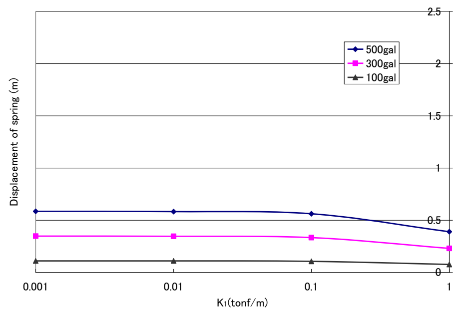


Figure 64-Displacement time history

(K_1=1tonf/m, Input 2Hz, acc.amplitude100gal)

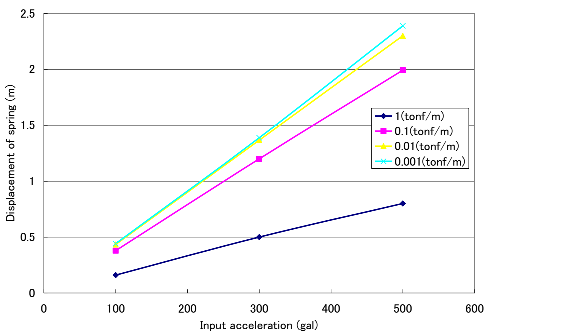


(1) 1Hz input

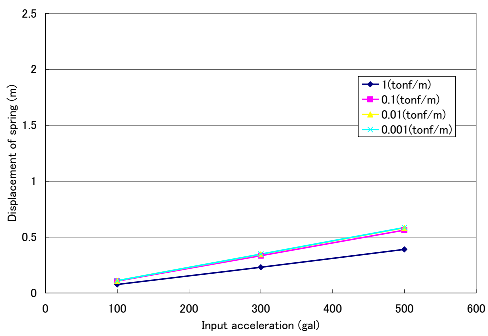


(2) 2Hz input

Figure 65-Relation between springy ratio and maximum displacement



(1) 1Hz input



(2) 2Hz input

Figure 66-Relation between input amplitude and maximum displacement

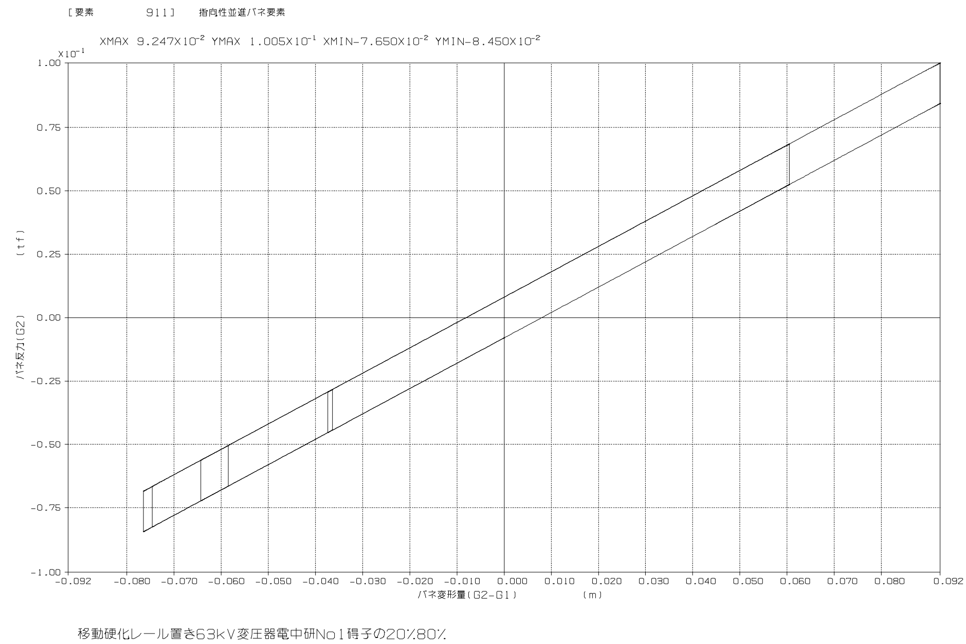


Figure 67-Displacement force history of connecting spring

(K_1=1tonf/m, Input: 2Hz, acc. Amplitude: 100gal)

In non-linear elastic analysis, if springy ratio in plastic range is low, i.e. rail is assumed to be smooth; displacement of connecting spring is amplified. In two-linear behaviour, connecting spring displacement isn't depended on input frequency (figure 65) and it is assumed that transformer rail isn't as smooth as railway. Springy ratio of k1=1e-3t/m is considered to prevent error increment. Figure 68 shows relation between input amplitude and maximum displacement in terms of input frequency. It is assumed that transformer body displacement or connecting spring displacement that is computed on the basis of input acceleration and allowable displacement have time distribution. μ of time distribution is shown in figure 69. Standard deviation is computed with assumption that difference between 1Hz and 2Hz is equal to $\mu \pm 3\sigma$. Moreover, it is assumed that mean allowable displacement is 1m and its variation factor is 0.1.

5) Results related to transformer with wheeled base

Figure 70 shows related fragility curve. As figure 68, HAZUS99 fragility curves are presented for comparison. As a result, fragility probability is more than the rupture probability of bracing bar due to movement of transformer body on rail.

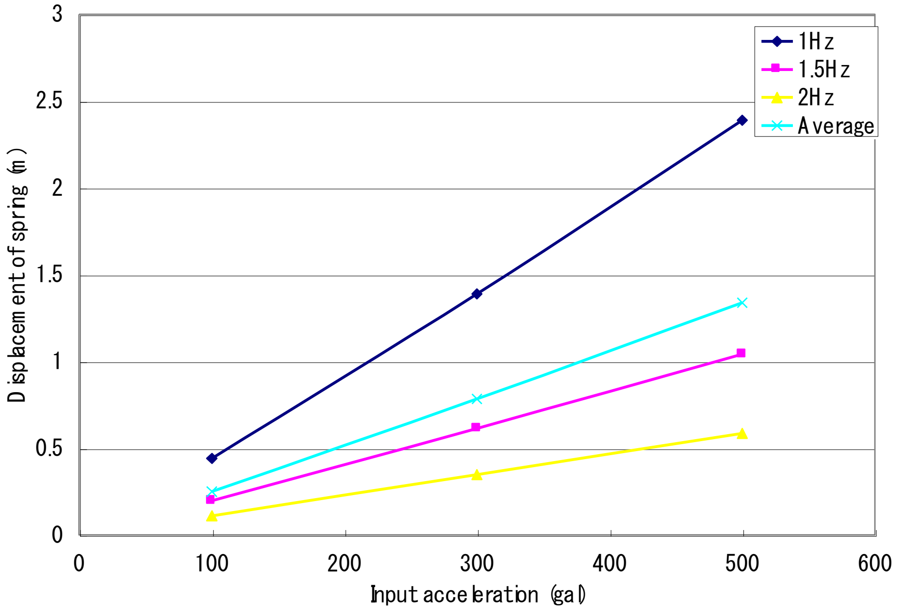


Figure 68-Relation between input amplitude and maximum displacement

6) Summary

Following fragility curves are compared in figures 69 and 70:

a) fragility curve of major mode of transformer placed on rail

b) fragility curve of major mode of transformer anchored with bracing bar

c) fragility curve of major mode of transformer

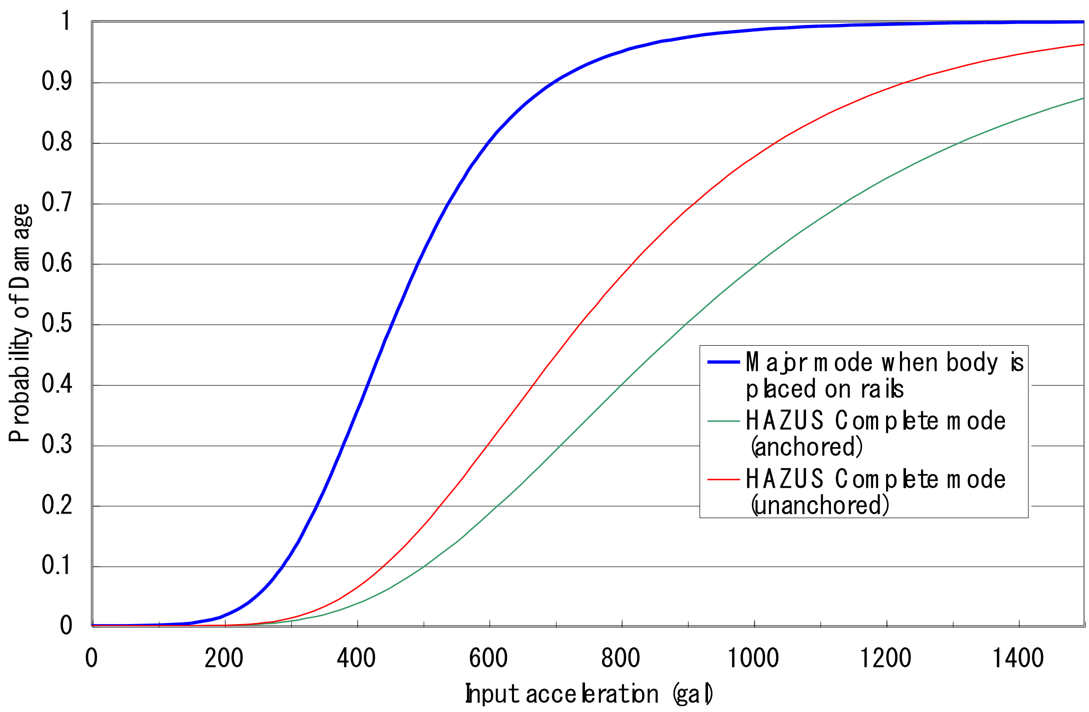


Figure 69-Fragility curve of transformer in major fragility mode

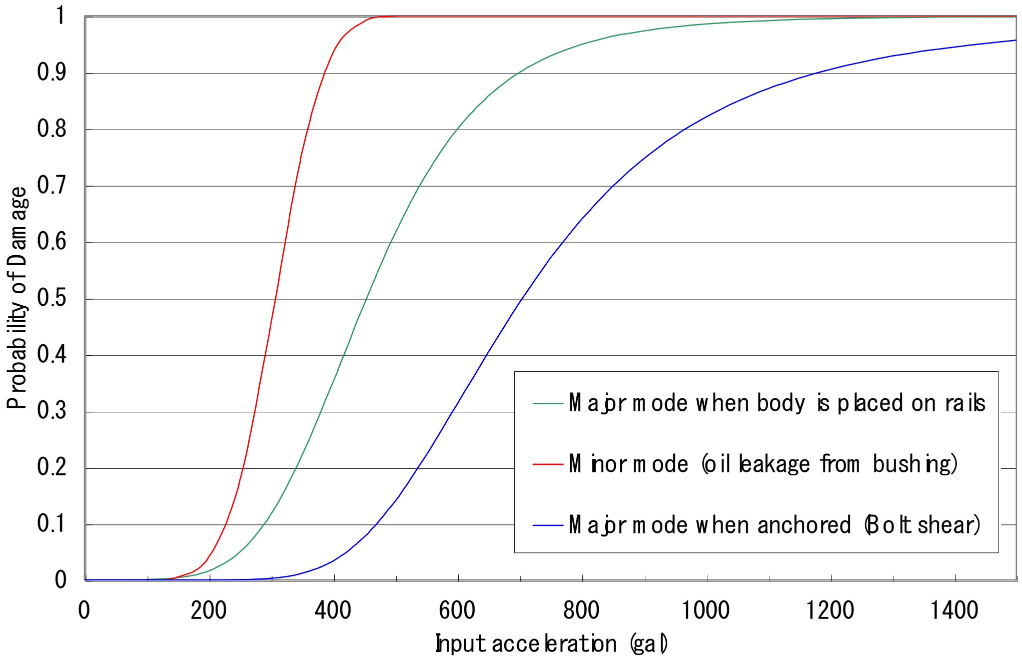


Figure 70-Fragility curve of 63.20kV transformer

2-2-5-Method of determination of fragility functions for 20.04 kV

a) Over-ground transformers

1) Assumption of general model

-Weight and dimension

Figure 71 shows an example of 20.04 kV transformers. Estimated dimension of transformer is shown in this figure. Weight of transformer and its oil is 2 and 1 ton, respectively.

if this transformer is to be assumed similar to 22.66 kV Japanese transformers in which oil is sealed with nitrogen, its minimum weight is 7 ton and capacity is 2000 to 3000 kV according to table 15. Comparison of transformer specification, capacity of Iranian transformer is lower.

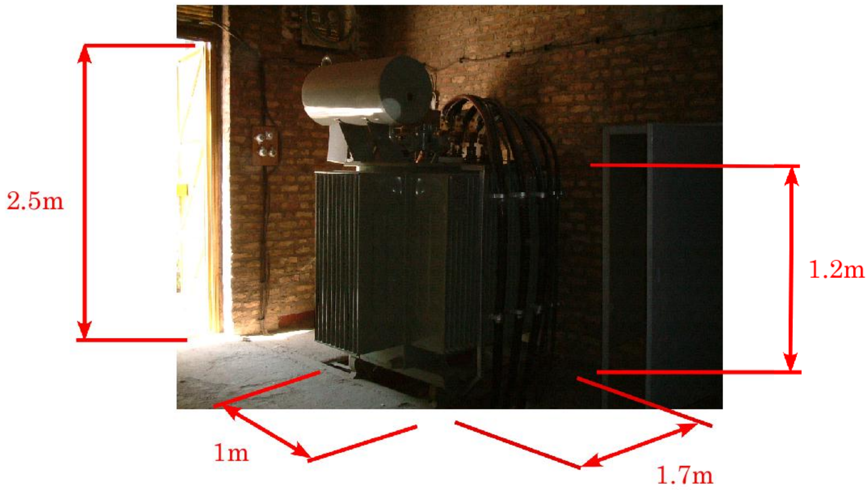


Figure 71-20.04kV

Table 15-Weight and dimension of 22kV Japanese transformer

Manufacturer	dimension X(width) x Y(depth) x Z(height)	weight
Toshiba	3.0m x 2.7m x 2.7m	7ton
Nissin Electric.	2.0m x 2.5m x 2.9m	9ton

Model of this transformer is shown in figure 72. With assumption of 1000kVA capacity, dimension of this transformer is as following:

Dimension:1705Mm×1225×3517=z ×y × x

Weight: 2880Kg

Therefore, analytic model specifications are assumed as following:

Dimension: z ×y × x =1600Mm×1200×1700

3000Kg:Weight:

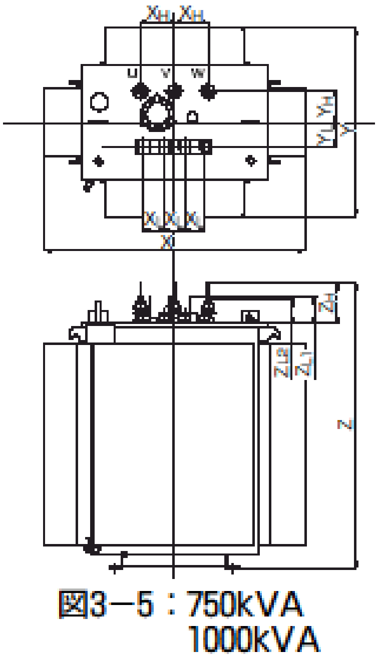


Figure 72-Model of Japanese transformer

Weight of the oil tank is assumed to be about 10 percent of total weight. Regarding bushing, 30 kg is considered for primary bushing and 15 kg is considered for secondary bushing. In Japan, weight of 6kV bushing is considered to be 15kg. Table 16 represents weight of various parts of the model.

Table 16- weight of various parts of the model

Main body	2.580ton
tank	0.3ton
bushing（30kg x 3 + 15kg x 3）	0.135ton
total weight involving oil	3.015ton

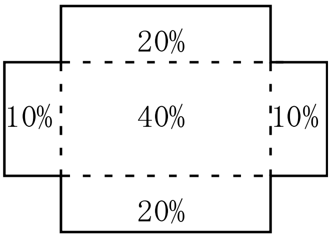


Figure 73-Weight distribution of various part of body

Bushing position

Figure 74 shows bushing position. Position of wheels is shown in figure 75. Bushing height is considered as figure 76. Figure 77 shows upper level of transformer.

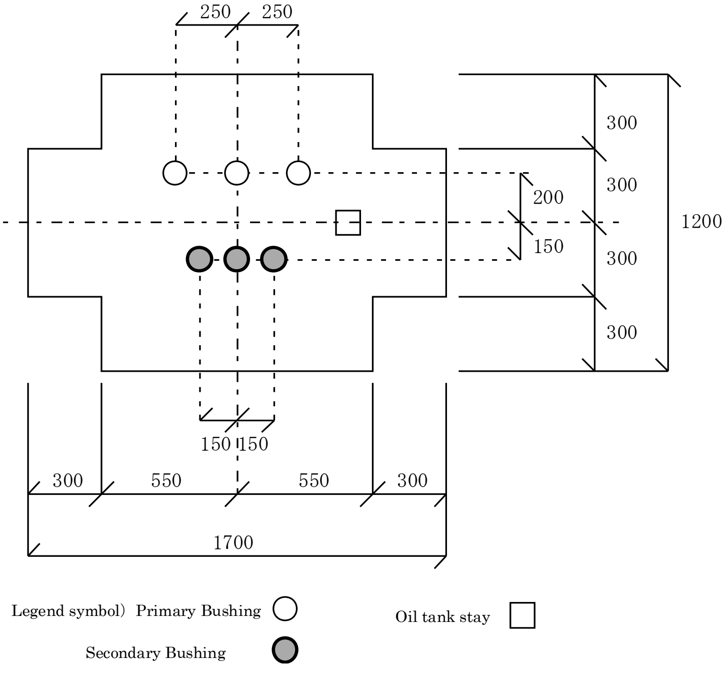
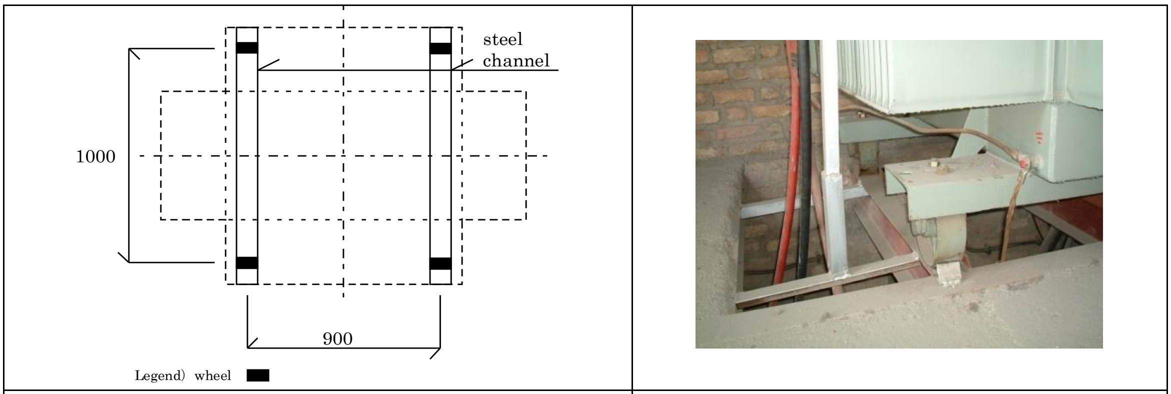
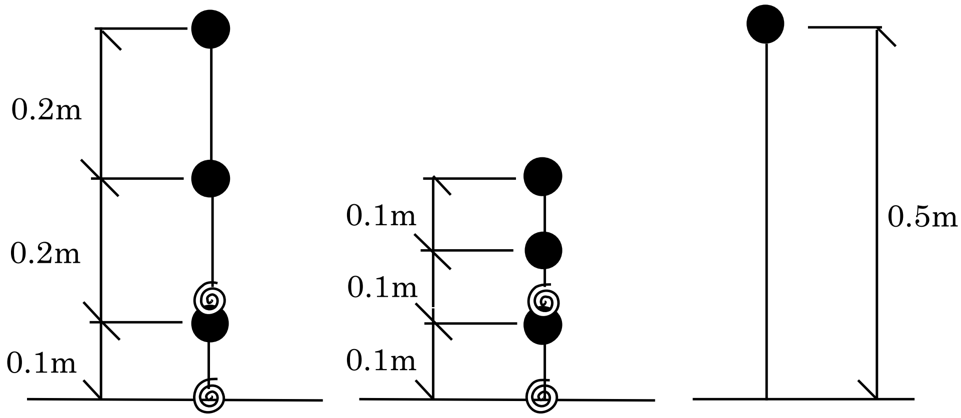


Figure 74-Bushing position



a)Position of wheel **b)situation of wheel**

Figure 75-Foundation status



a)Primary bushing **b)Secondary bushing** **c)oil tank**

Figure 76-Lateral view of bushing and tank

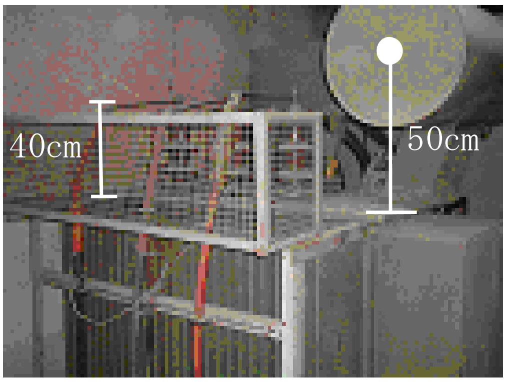


Figure 77-Upper level of transformer

2) Analytical model

Figure 78 shows analytical model of transformer. Main body and bushing were constructed with linear beam elements. Rolling springs used for bushing and main body was positioned on a wheeled metallic bar that was modelled with non-linear connecting elements.

-Bushing specifications

Bushing specifications are presented in tables 17 and 18 and figure 68 for analysis. Figure 69 shows relation between springy ratio of rolling spring and bushing flange dimension. It is assumed that d=h=10cm , t=1cm and springy ratio to be calculated on the basis of table 18.

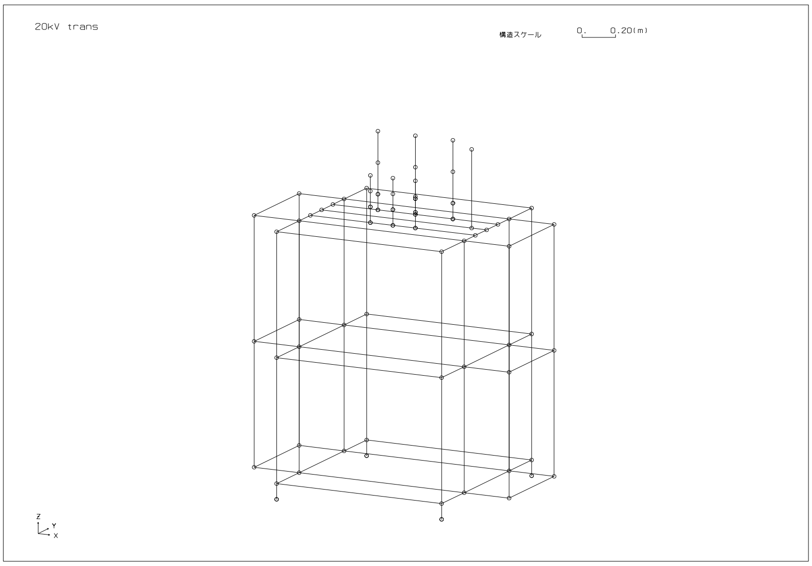


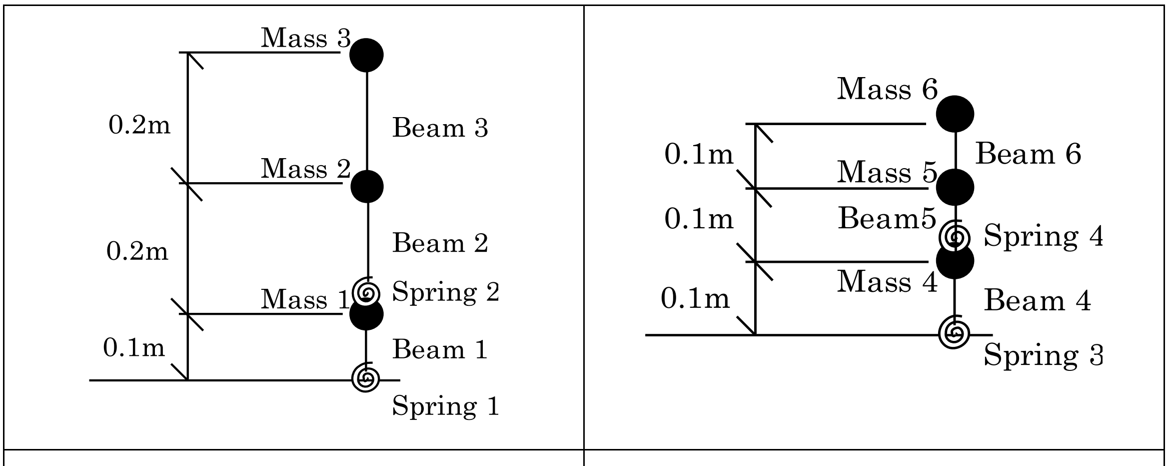
Figure 78-Analytical model of 20.0.04 kV transformer

Table 17-Specification of beam elements

bushing	element	material	cross section	inertial moment	elastic module	Poisson factor	damping ratio
primary	Beam1	Steel pocket	1.4E-02	5.3E-06	2.1E+07	0.3	0.05
	Beam2	Porcelain	5.0E-03	3.0E-06	7.4E+06	0.23	0.05
	Beam3	Porcelain	5.0E-03	3.0E-06	7.4E+06	0.23	0.05
secondary	Beam4	Steel pocket	1.4E-02	5.3E-06	2.1E+07	0.3	0.05
	Beam5	Porcelain	2.8E-03	2.0E-06	7.4E+06	0.23	0.05
	Be am6	**Porcelai n**	**2.8E-03**	**2.0E-06**	**7.4E+06**	**0.23**	**0.05**

Table 18-Spacification of rolling spring

	element	position	springy ratio (tonf*m/rad)	damping ratio
primary	Spring 1	Bottom of Pocket	670	0.02
	Spring 2	Bottom of porcelain	500	0.02
secondary	Spring 3	Bottom of Pocket	670	0.02
	Spring 4	Bottom of porcelain	500	0.02



(1)primary bushing **(2) secondary bushing**

Figure 79-Analytical model of bushing

-Foundation specifications

It is assumed that transformer is situated on wheeled metallic bar. Similar to 63.20 kV transformer, non-linear connection is used for displacement modelling in three-directions. Rolling degree of freedom is locked and bushing end is fixed. According to performed visits, wheel brake was situated next to it on the metallic beam. Figure 70 shows connection element specification in the model involving brake. Weight of wheel itself is 750 kg. It is assumed that the wheel moves when lateral force component of earthquake in the vertical direction of brake gradient is more than weight in the direction of brake gradient. In figure 80, P1 is considered as following:

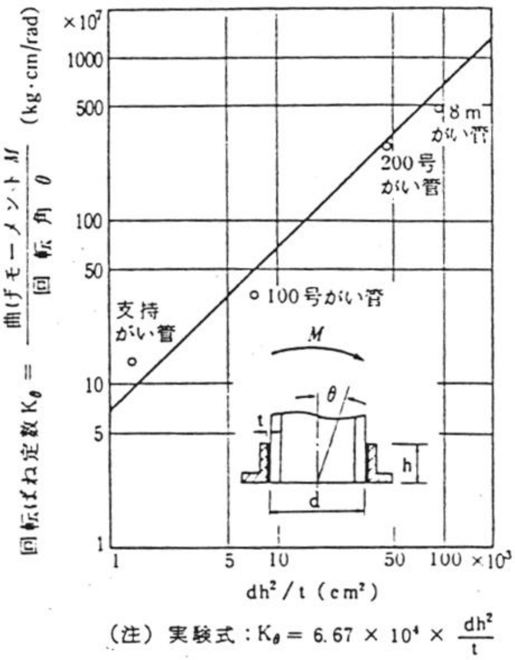


Figure 80-Springy sate in flange part

P_1=750 tanf × tan 45 = 1/21 tan f (5)

If wheel movement is more than L_1, it is assumed that wheel ascends from brake and L_1 is equal to 5cm. Springy ratio K_0 and K_2 are assumed as following:

K0 = - K2 = 1/2 E + 3 t/m (6)

While K_1, K_3 and K_4 are assumed to be little value as small as $\frac{K_0}{10000}$. Specifications of connection element that intercept rail are shown in figure 81. In this direction, if lateral force is higher than maximum static friction force, wheel will move. It is worthwhile to note that there isn't any brake or connection to prevent sliding. Static friction coefficient M_S is assumed to be equal to 1 and wheel weight is reduced to half due to earthquake acceleration. In this case, maximum static friction force P1 is equal to:

$$P_1 = 0/75 \times \frac{2}{3} \times 1 = 0/5 \tan f \qquad (7)$$

Sliding friction coefficient M_K is assumed to be half of static friction coefficient μ_s and $P_2 = 250kgf$. Primary hardness K_0 is given as following:

$$K_0 = 0/5E + 3TANf/m \qquad (8)$$

K1 value is assumed to be equal to $\frac{k_0}{10000}$ that is small sufficiently. It is assumed that in vertical direction, if vertical earthquake force is bigger than weight, wheel rises. Moreover, K0 assumed to be equal to 3tanf/m + 0.5E to prevent movement toward bottom.

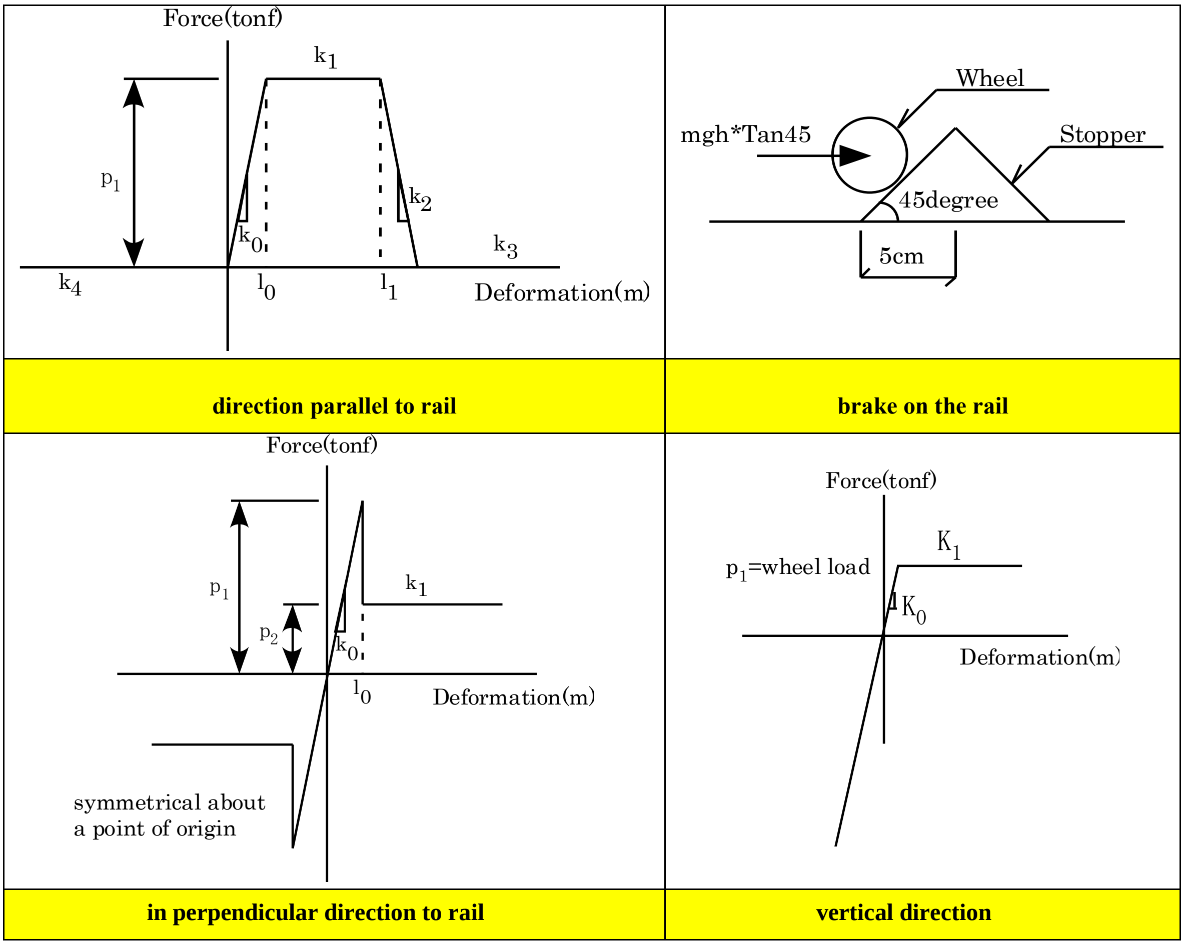


Figure 81-Specification of connection element

Input of sustainable three sine waves system is considered with frequencies of 2, 1 and 0.5. In severe fragility, transformer movement is perpendicular to rail. If brake function is good, high earthquake force must be created to rise the wheel therefore its probability is very low and it is confirmed by analytical investigations.

In the direction perpendicular to rail, it is assumed that sliding more than 5cm leads to outgoing from rail. In this case, transformer falls and bushing is threatened severely. In the case of allowable sliding length, normal distribution with mean of 5cm and variation factor of 0.2 is considered. Minor fragility mode is considered as cracking in porcelain. Figure 82 shows allowable stress of bushing bending that its maximum value is 200 kg/m^2. It is assumed that cracking occur in 1% of this stress. Associated variation factor is considered to be 0.15. After analysis of eigenvalues, natural frequency of under body connection spring was obtained more than 10 Hz and natural frequency of bushing itself was obtained equal to 30Hz, so resonance probability is very low.

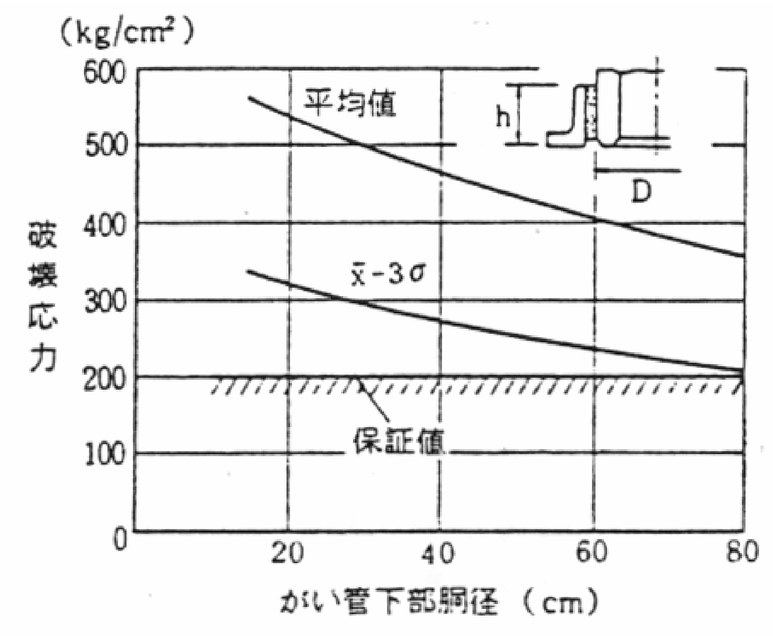


Figure 82-Allowable bending stress of bushing

3) Results

Figure 83 shows the relation between input acceleration amplitude and sliding distance perpendicular to rail axis on the basis of input frequency parameter. As apparent in the figure, sliding increase with increment of frequency so results related to frequency of 5Hz is used for reliability. Figure 84 shows fragility curve of major fragility mode that is outgoing from rail. It is assumed that rail movement involve normal distribution with variation factor of 0.4. Variation factor of allowable value of movement is the same and its mean is 5cm. Low voltage posts in general fragility mode are given in figure 85 for the sake of comparison that one of them is related to seismic design and another lack any seismic design. More vulnerable fragility curve in anchored transformer mode is obtained from HAZUS99 model.

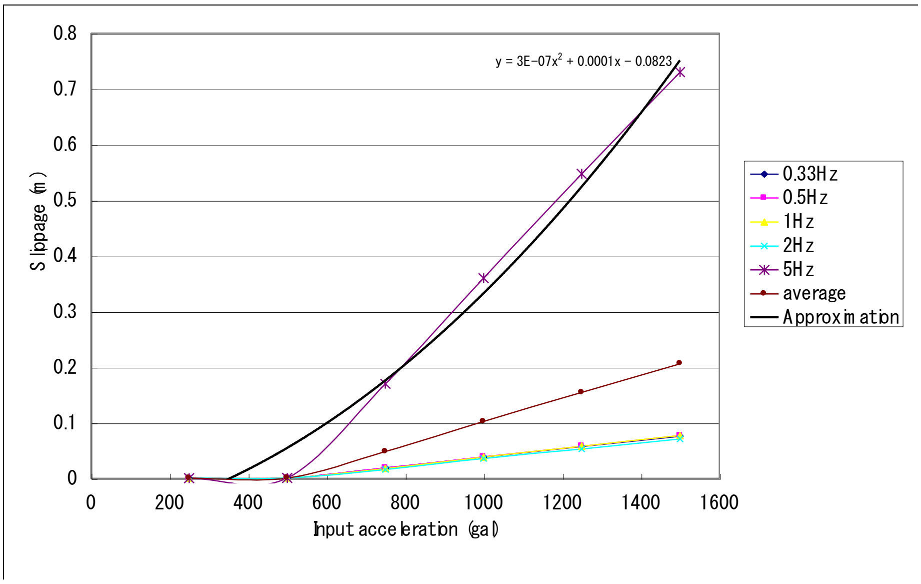


Figure 83-Sliding distance in the direction perpendicular to rail axis

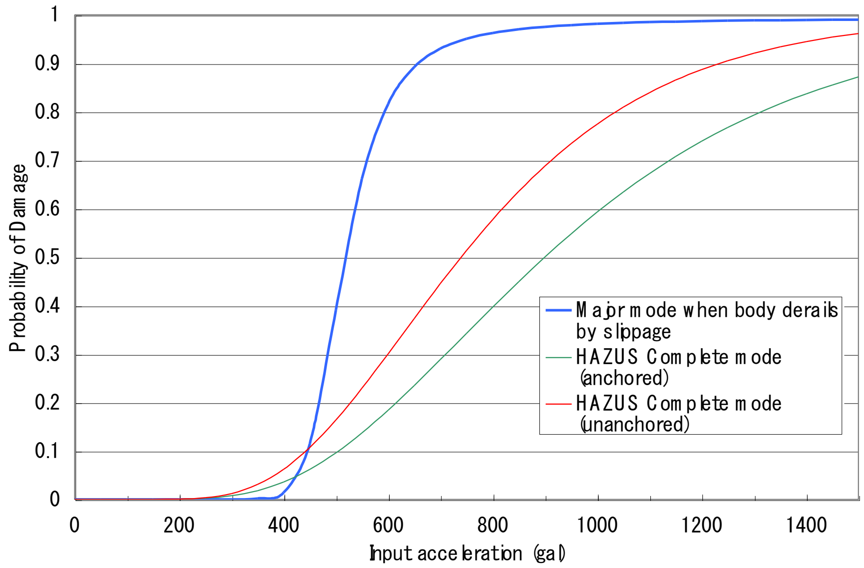


Figure 84-Fragility curve of major mode of 20.0.04 kV transformer

Figure 85 shows relation between bending moment and input acceleration amplitude for primary bushing. Moment with bending stress factor was obtained in section module. Since primary bushing is considered more vulnerable than secondary bushing, cracking of primary bushing is accounted as minor fragility mode. Bending moment value is equal to 0.18m. Figure 86 shows fragility curve of minor mode in comparison with HAZUS99 curves.

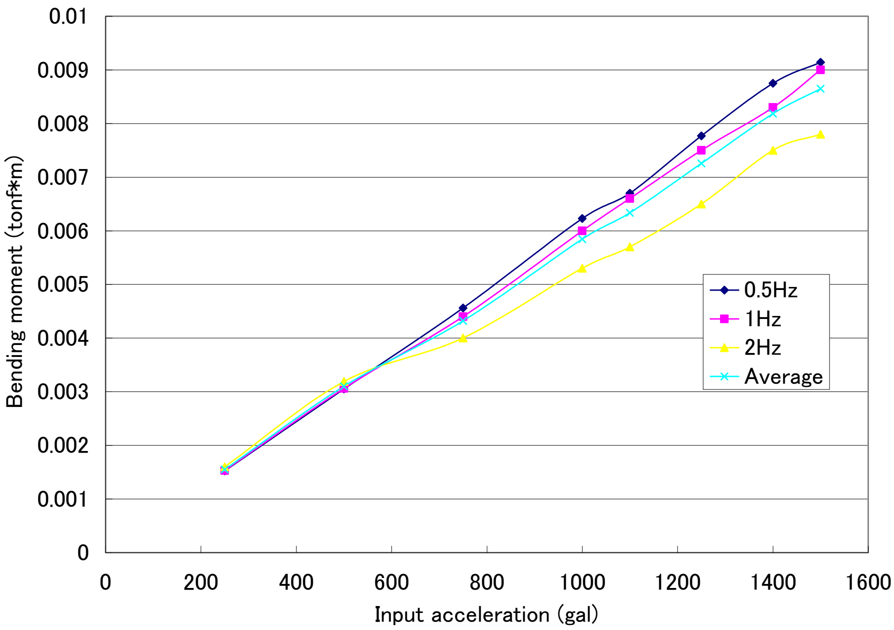


Figure 85- Relation between bending moment and input acceleration amplitude for primary bushing

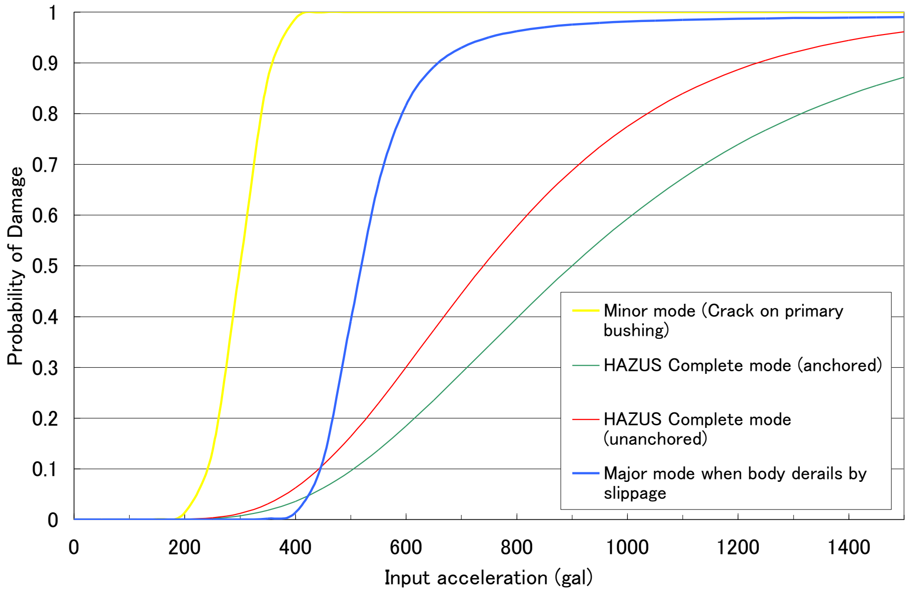


Figure 86-Fragility curve of minor mode for 20.0.04 transformer in comparison with HAZUS99 curves

2-2-6-Fragility curve of 230.63kV current transformer

a) Introduction

Function of current transformers is to decrease current. Three-dimensional modal and time history analysis was performed under accelergraph of the Kobe earthquake. Moreover, dynamic analysis performed under three sine waves with frequency equal to natural frequency, in order to investigate resonance phenomenon in equipment. Fragility curve was prepared to evaluate vulnerability. In this case, major, moderate and minor modes are presented, as well.

b) Current transformer model

Current transformer model was prepared according to figure 87. In general, these equipments are classified according to bushing shape and geometry. Bushing section of these transformers is variable and its specifications are presented in table 87.

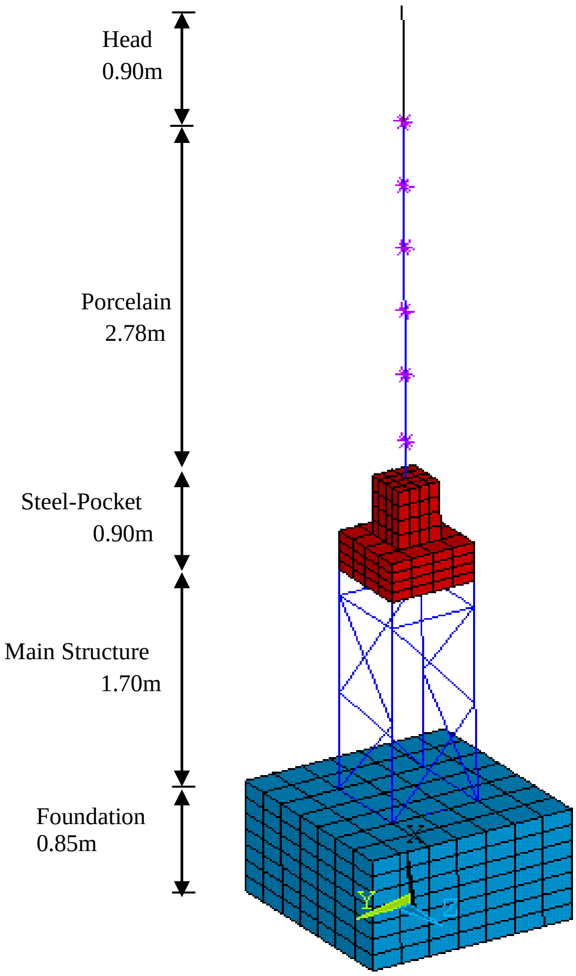


Figure 87-Three-dimensional finite element model of current transformer

It is assumed that equipment base is fixed in four corners. Each fixed base involves 2 bracing bar with diameter of 16mm with ASTM-A307 material. Table 19 presents other structural and geometric specifications of the model.

Table 19-Structural specifications of transformer

Specifications	dimension
dimension of main structure	0.70*0.70
dimension of foundation	1.5*1.5*0.85
height of main structure	1.7
total length of bushing	3.68
length of porcelain part	2.78
height of main structure from foundation	6.13
number of section specifications	21
base type	Fixed
section of bracing elements	L50*50*6
section of pillar elements	L65*65*8
elastic module of steel section	206000
elastic module of porcelain section	99800
pedal diameter of porcelain (CM)	47.5
thickness of porcelain (CM)	3
head diameter of porcelain	45
diameter of bracing bar	16
thickness of metallic plate above tank	20

In order to modeling equipment, main structure, metallic ca, porcelain and its mass and head are modelled by three-dimensional elements, shell element, beam element, concentrated mass element and pipe element respectively. Modelling was performed using ANSYS6.1. Details of metallic gasket are presented in figure 88.

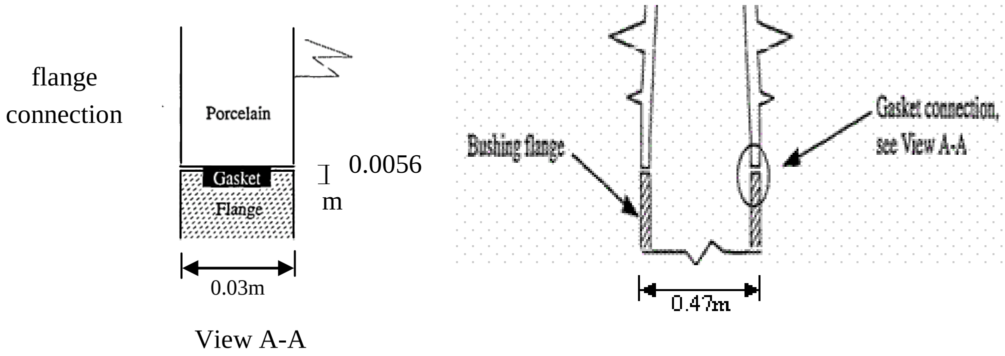


Figure 88-Details of gasket connection in current transformer

c) Modal analysis

Modal analysis was performed to calculate natural vibration frequencies. The Ten first obtained modes are presented in table 20. In the two first modes, bushing is undergone deformation of upper metallic cap plate as its solid rotation. Vibrations of the ten first modes are presented in figures 89 to 98.

Table 20-Natural frequencies of current transformer in terms of Hz

Mode Number	Mode No.10	Mode No.9	Mode No.8	Mode No.7	Mode No.6	Mode No.5	Mode No.4	Mode No.3	Mode No.2	Mode No.1
Frequency	97.593	72.835	72.786	69.404	55.124	22.314	22.171	6.2707	2.8868	2.8865

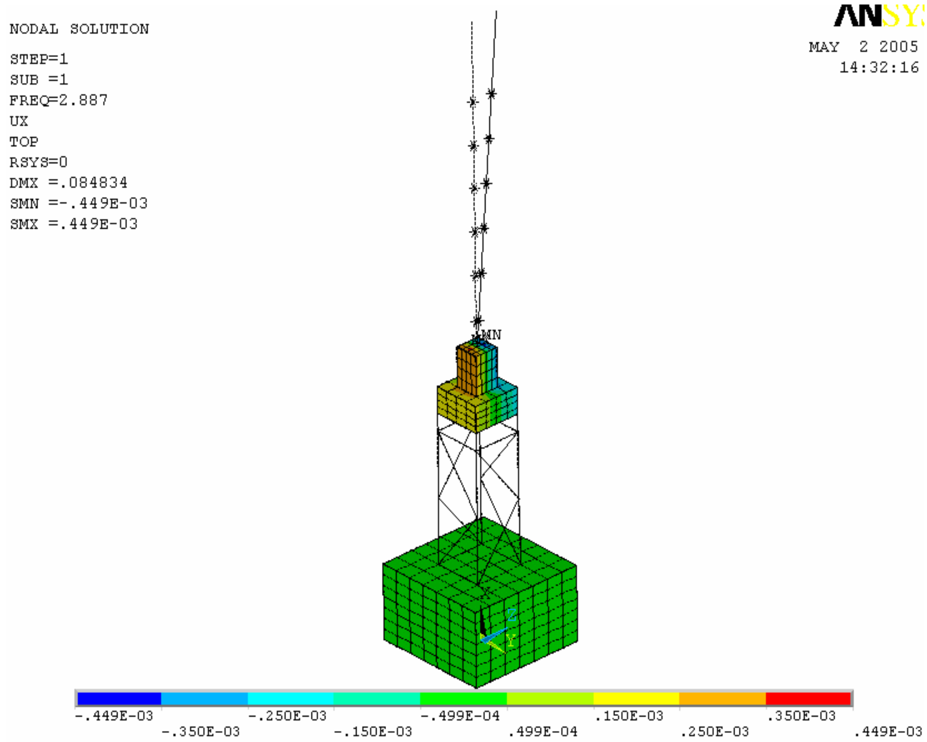


Figure 89-Shape of the first mode of current transformer with frequency of 2.8865 Hz

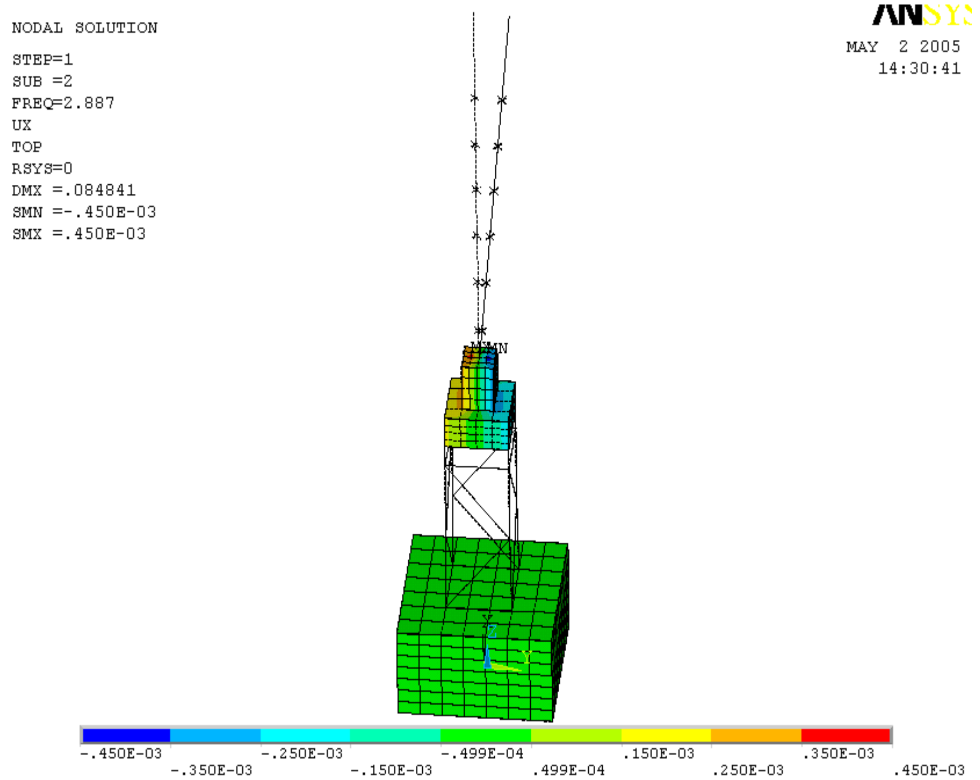


Figure 90-Shape of the second mode of current transformer with frequency of 2.8868 Hz

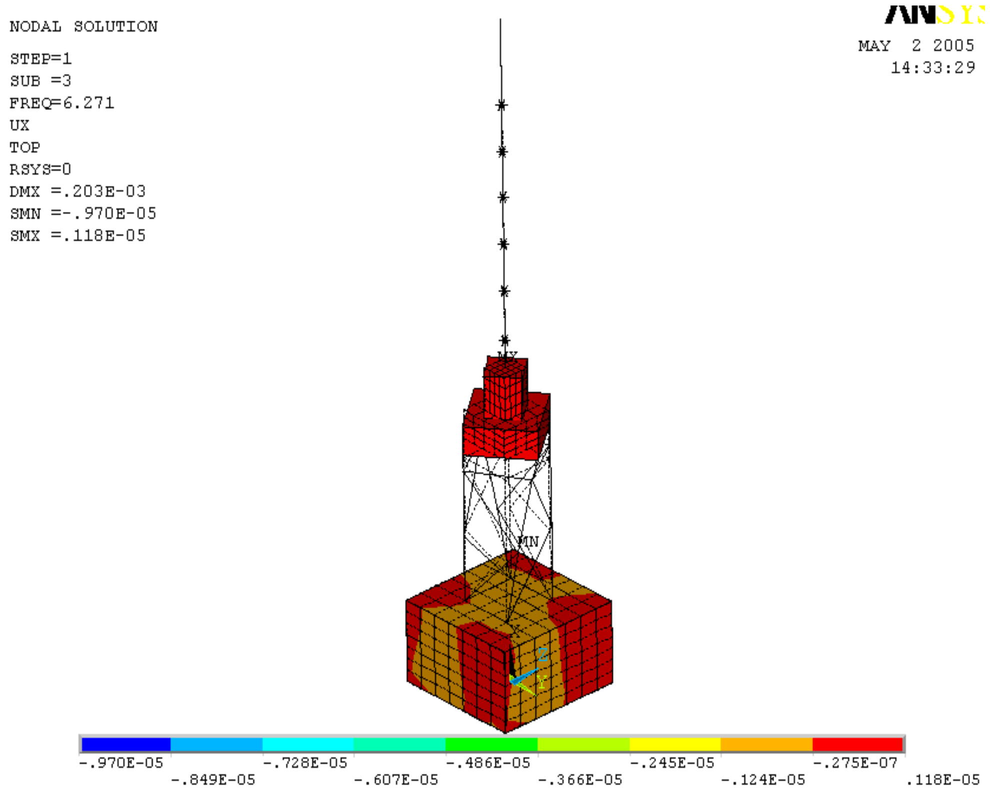


Figure 91-Shape of the third mode of current transformer with frequency of 6.271 Hz

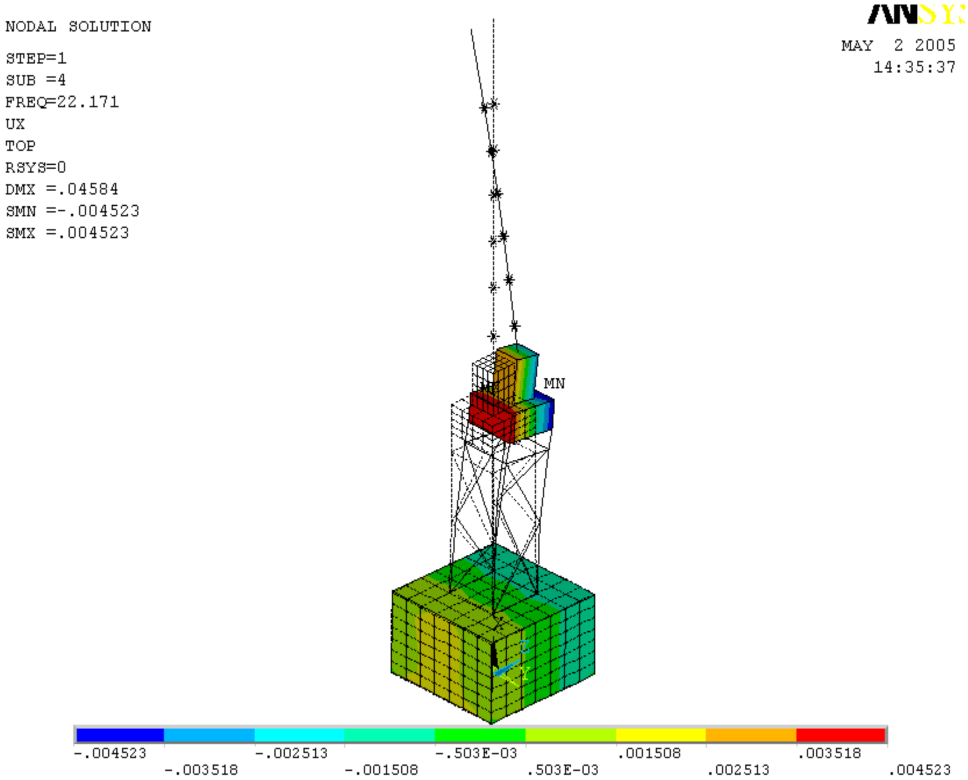


Figure 92-Shape of the fourth mode of current transformer with frequency of 22.171 Hz

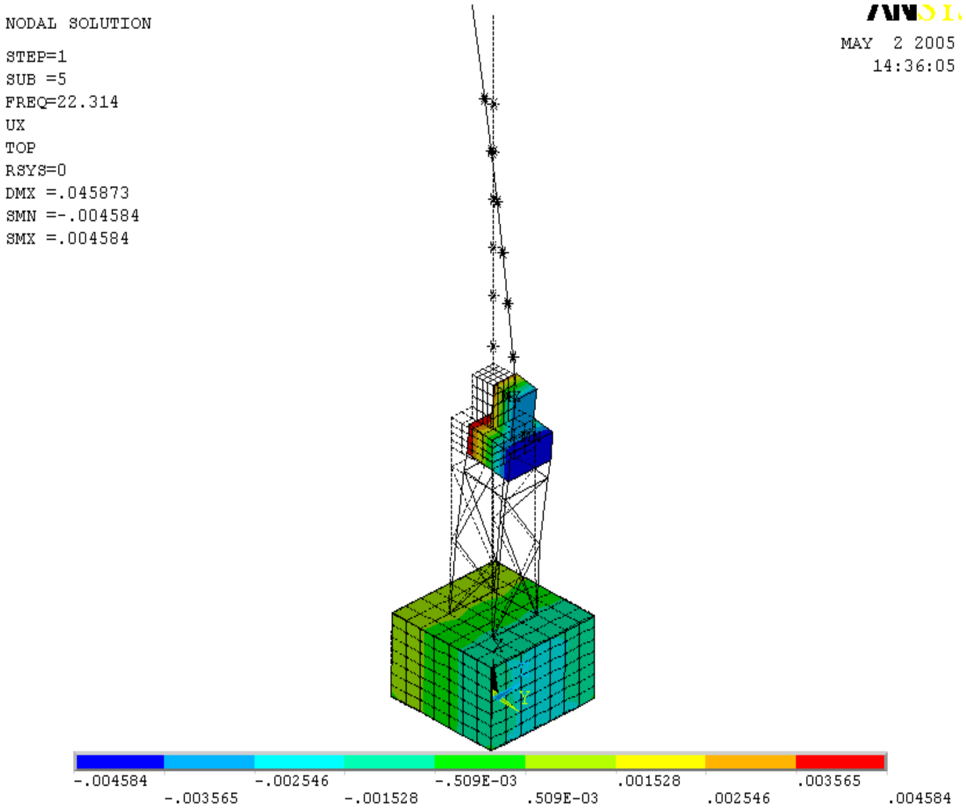


Figure 93-Shape of the fifth mode of current transformer with frequency of 22.314 Hz

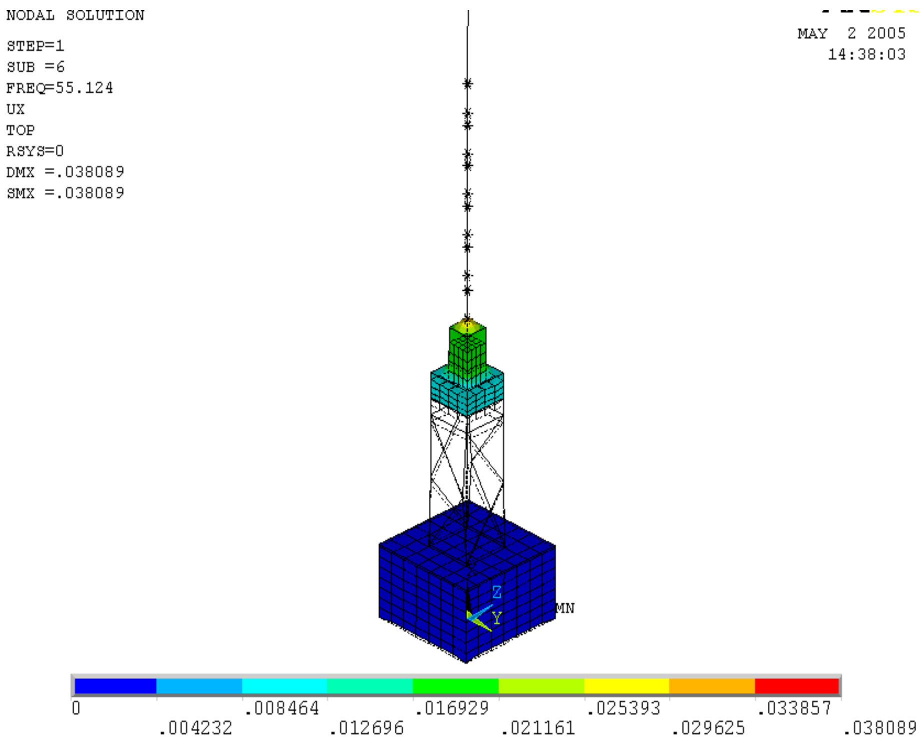


Figure 94-Shape of the sixth mode of current transformer with frequency of 55.124 Hz

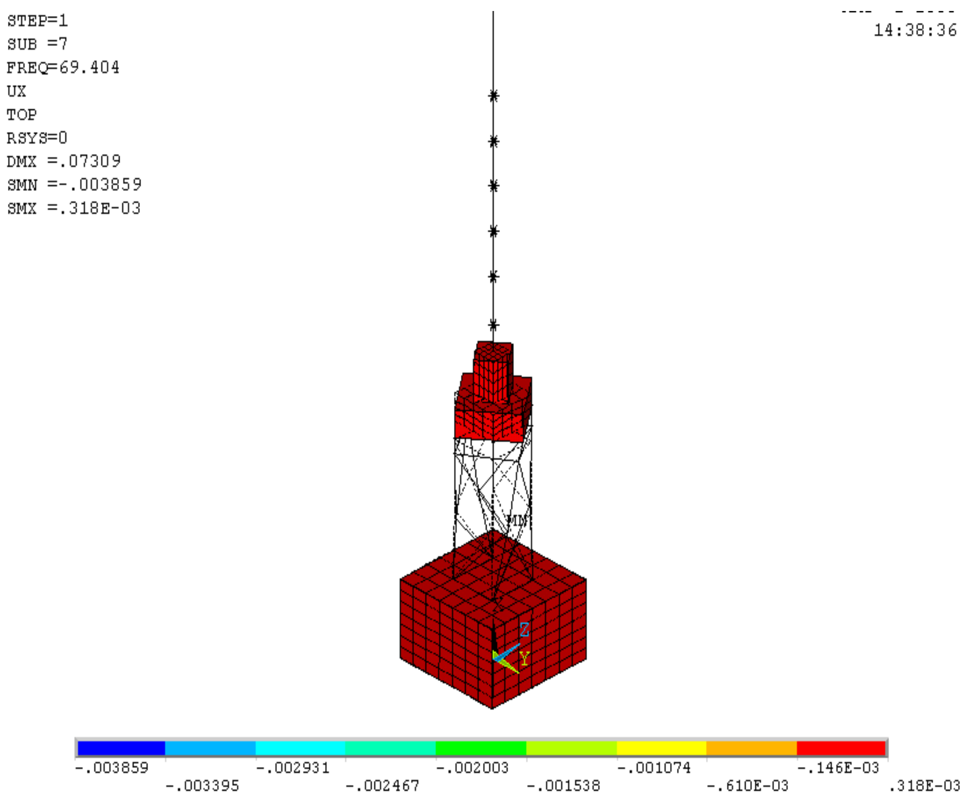


Figure 95-Shape of the seventh mode of current transformer with frequency of 69.404 Hz

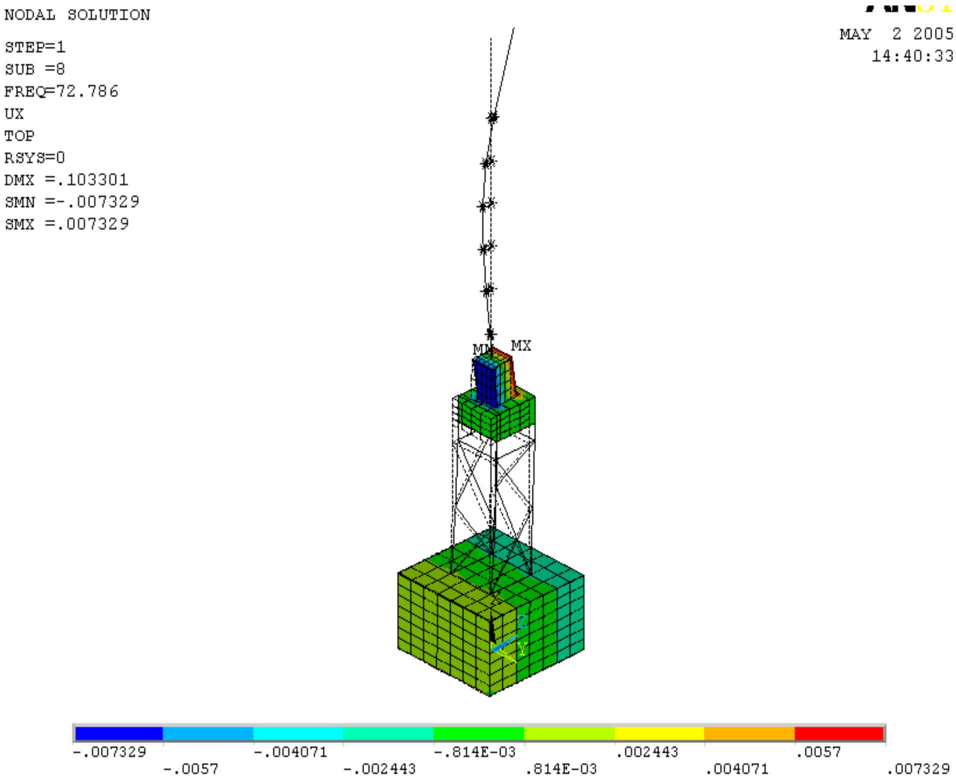


Figure 96-Shape of the eighth mode of current transformer with frequency of 72.786 Hz

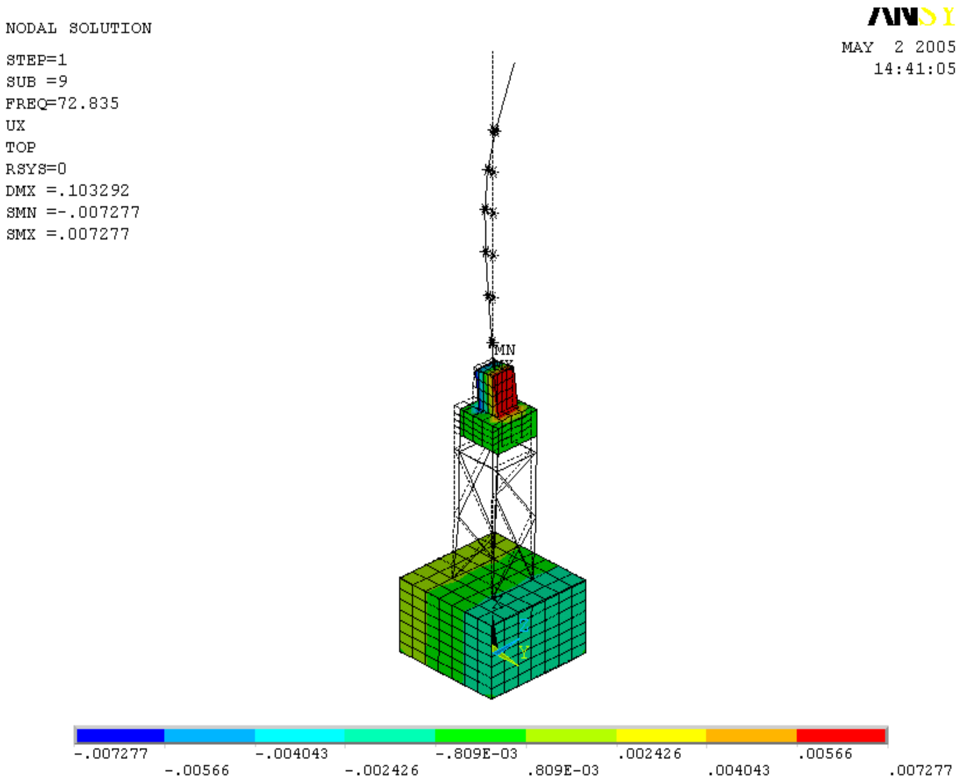


Figure 97-Shape of the ninth mode of current transformer with frequency of 72.835 Hz

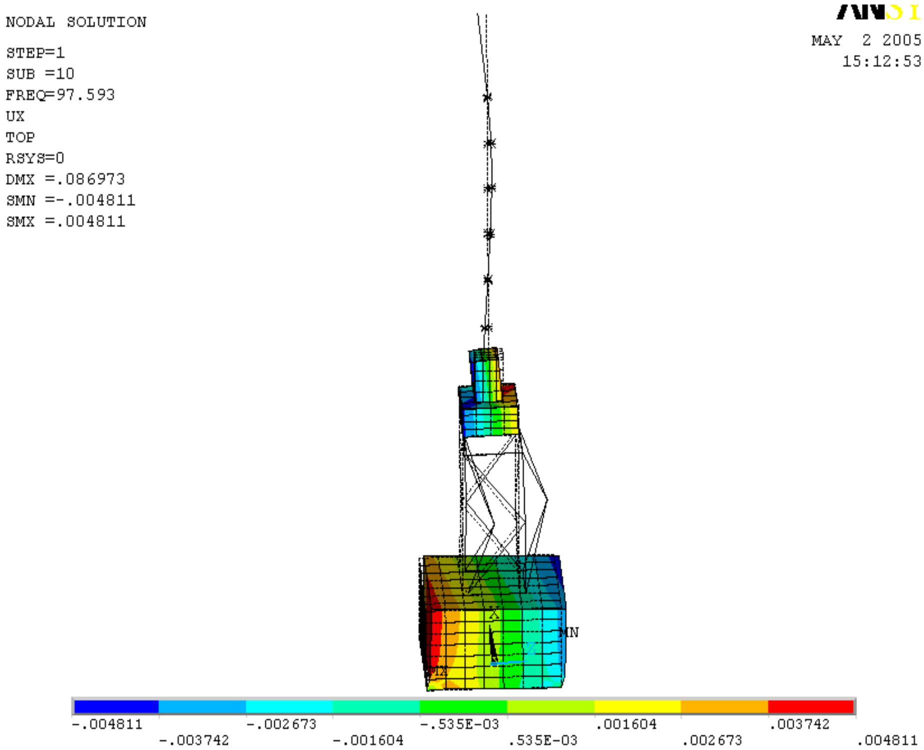


Figure 98-Shape of the tenth mode of current transformer with frequency of 97.593 Hz

d)Time history analysis

Two linear time history analyses were performed that one of them was performed under the Kobe earthquake and another was performed under sine waves (with common frequency equal to 2.887 Hz and maximum acceleration of 0.5g to investigate resonance phenomenon on the basis of the Japanese code for bushing analysis). Lateral displacements of various levels of current transformer under these loadings are shown in figures 99 and 100.

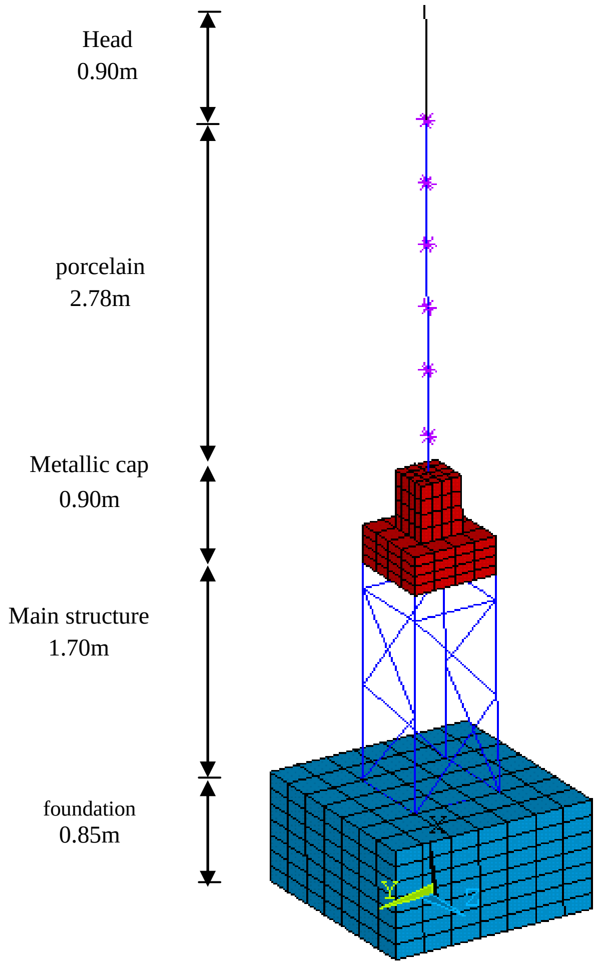


Figure 99-Lateral displacement in various levels under the Kobe earthquake

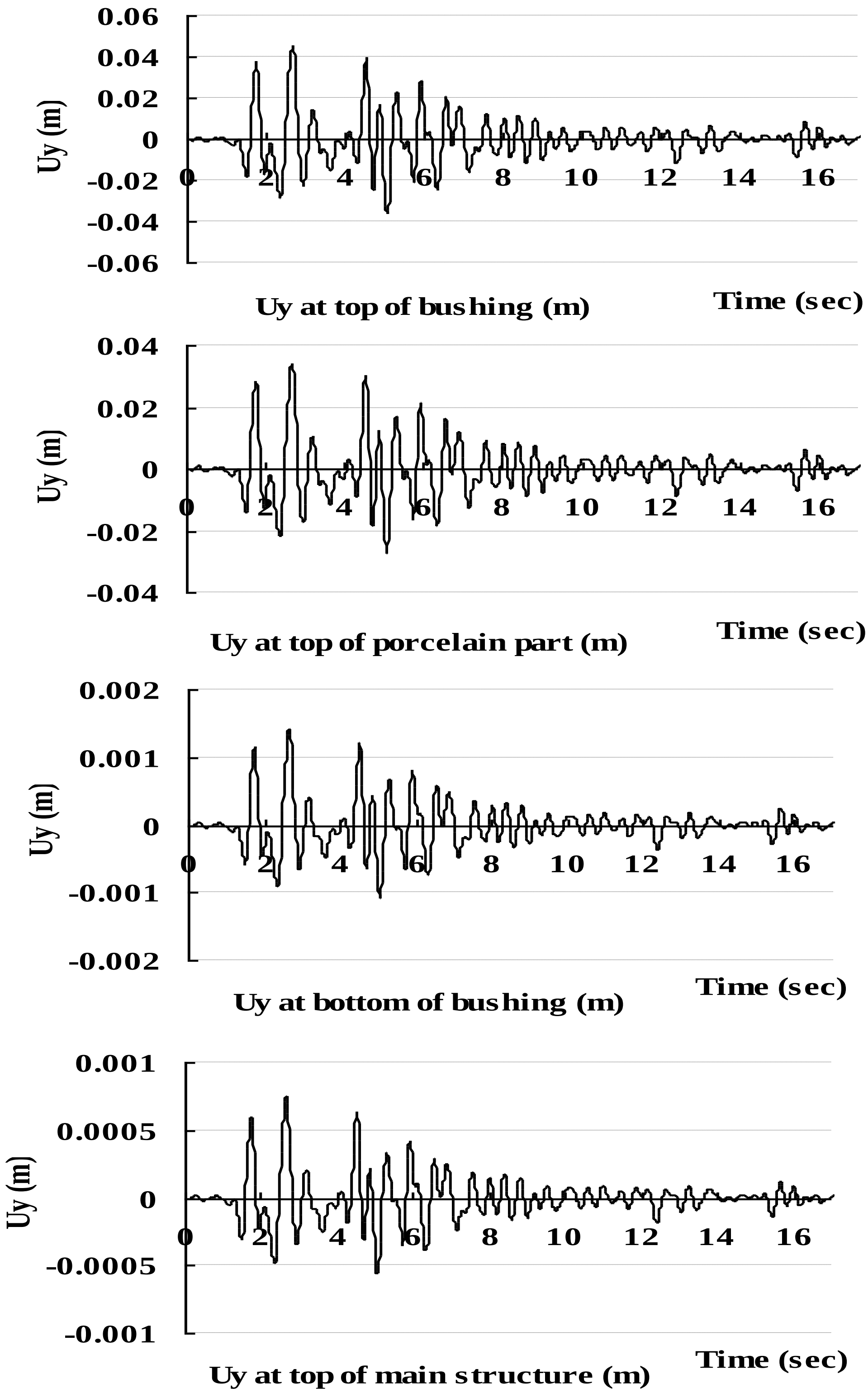


Figure 100-Lateral displacement in various levels under the Kobe earthquake

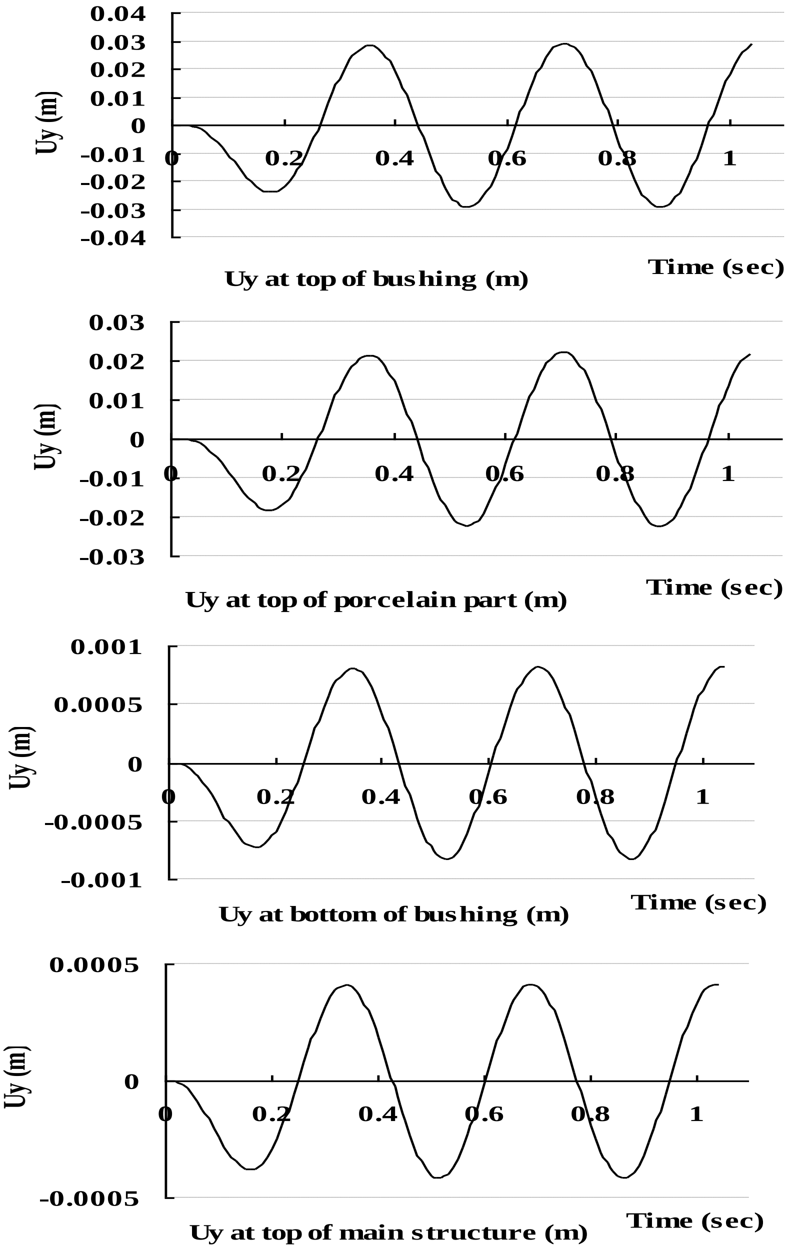


Figure 101-Lateral displacement in various levels under sine waves with frequency equal to the first frequency of natural vibration

e) Fragility function

Fragility functions for minor, moderate and major modes were obtained on the basis of above-mentioned three-dimensional linear analyses. Normal distribution with standard deviation and mean appropriate with fragility mode was used for allowable values and variation factor equal to 0.2 was assumed for them.

f) Minor fragility

Minor fragility in this equipment is as rising or interaction of connection between end of porcelain and metallic cap that leads to oil leaking. This interaction is due to vertical displacement and soil rotator motion which the latter is more than the former and so is considered as criterion. Soil rotation is defined as lateral relative displacement between top and bottom of porcelain part. According to results of the experiments, its allowable mean is assumed to be 1mm and soil relative displacement between top and bottom of porcelain that lead to oil leaking is 11.62mm. Interaction in connection is calculated on the basis of soil lateral relative displacement as following:

$$\frac{\text{Connection interaction}}{\text{Porcelain diameter}} = \frac{\text{Lateral relative displacement}}{\text{Porcelain length}}$$

Relative displacement and its relative value in y direction is the most critical value. Maximum lateral displacement in bushing between initial and end of porcelain in y direction for the Kobe earthquake with maximum acceleration of 0.8178g was obtained equal to 33mm but for tree sine waves with maximum acceleration of 0.5g is calculated equal to 21.4 mm and so, sine loading is more critical. Accelerations associated with mean and standard deviation are 0.271and 0.054g, respectively. Therefore, fragility function is obtained as accumulative distribution function of the response normal distribution.

g) Moderate fragility mode

Moderate fragility mode is defined as fracture of porcelain in main bushing due to bending moment. Related criterion of lateral displacement is lower than bending moment depends on type of connection between porcelain and metallic cap but for higher displacements, stress concentration in the direct contact of porcelain and metallic part is according to figure 87. This contact area is considered about 3% of total area during removal of load.

Maximum stress is considered based on maximum bending moment and axial force in connection. Allowable mean stress in porcelain is assumed to be 14.34 MPa. Maximum available concentrated stress in contact surface is 15.81 MPa, as well. Acceleration values associated with mean allowable stress of 14.34 MPa with standard deviation of 0.029 MPa are 0.742g and 0.148g, respectively.

f) Major fragility mode

Major fragility mode is defined as fragility in bracing bars of supporting structure base. Main structure has 4 bases situated in four corners, each have two bracing bar with diameter of 16mm of ASTM-A307 material and their capacity is controlled on the basis of shear and extension. Tensile fracture in current transformers is more critical. Allowable tensile stress of these bracing bars is 92.95 MPa, according to Iranian standard.

Tensile force of maximum response in the most critical base is 26.1 kV that leads to tensile stress of 92.55 MPa. Mean and standard deviation of acceleration for allowable shear stress of 92.95 MPa is 0.821g and 0.164g respectively. Fragility function of major fragility mode is accumulative distribution function of normal distribution curve.