EARTHQUAKE RESISTANT DESIGN
OF
ELECTRIC POWER SYSTEMS

Prepared for
Japan Society of Civil Engineers

EDITORIAL STAFF

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1. INTRODUCTION

A complete electric power system consists of the power generating stations, substations, energy control center, system control and data acquisition system, high-voltage transmission lines, distribution systems and supporting structures. These may be above-ground and/or in-ground structures.

There is no criterion that regulates consistently the earthquake resistant design method of all structures in the electric power system. For structures of each part in the system, however, the design method is provided by laws, design codes and criteria established by the relating organizations and self-constituted design criteria of a company.

Among a variety of the structures, outlined here are the earthquake design methods for important substation facilities, transmission steel towers and transmission tunnels. Although buried pipes are also important, they are not mentioned here since the design method is similar to that of the gas pipelines.

2. SUBSTATION FACILITY

2.1 General

This section specifies the design method and the design earthquake force associated with the fundamental of standard earthquake-resistant design.

2.1.1 Reference earthquake force for design

Reference earthquake forces on the ground surface for earthquake-resistant design in this section are as follows.

(1) Horizontal peak ground acceleration 0.3 G

NOTE: Vertical acceleration is generally neglected. However, a half of the horizontal acceleration may be taken as vertical acceleration depending on the structural condition and performance of subject facilities.

(2) Range of predominant frequency of the ground 0.5～10 Hz

2.1.2 Regional condition

Regional condition is not considered in general.

2.1.3 Standard ground condition

Standard ground condition is defined for the case where the following design earthquake force can be applied in the earthquake-resistant design of outdoor porcelain-clad equipment and transformers. That is:

$$S \text{ wave velocity } (V_s) \geqq 150 \text{ m/s} \quad \text{or} \quad N \text{ value} \geqq 5$$

If the above condition is not satisfied, a specific design must be employed.

2.1.4 Combination of external force

Combination of external force such as wind force, electrical operational force, is not basically considered.

2.2 Earthquake resistant design of outdoor porcelain-clad equipment

2.2.1 Types of facility

Switchgears, current transformers and cable heads for transmission to be placed outdoor.

2.2.2 Design method

Dynamic design procedure on the basis of the pseudo resonance method should be applied.

2.2.3 Seismic input

(1) Acceleration

0.3 G Horizontal acceleration

(2) Wave profile

Three (3) cycles of sinusoidal wave whose frequency is equal to
the resonant frequency of the structure model

NOTE: If the natural frequency of the equipment is lower than 0.5 Hz or higher than 10 Hz, the frequency of design wave should be 0.5 Hz and 10 Hz respectively.

(3) Excitation Point of design earthquake force

Bottom of the supporting frame structure

2.3 Earthquake resistant design of outdoor transformer

This article tentatively specifies the earthquake-resistant design of outdoor transformers: This specification should be improved based on future development and study.

2.3.1 Types of facility

Transformers to be placed outdoor.

2.3.2 Design method

(1) Bushing

Dynamic design procedure on the basis of the pseudo-resonance method should be applied.

(2) Transformer (bushing is not included)

Static design method should be applied.

2.3.3 Seismic input

(1) Bushing

a. Acceleration

0.5 G Horizontal acceleration

b. Wave Profile

Three (3) cycles of sinusoidal wave whose frequency is equal to
the resonant frequency of the structure model

NOTE: If the natural frequency of the bushing is lower than 0.5 Hz or higher than 10 Hz, the frequency of design wave is 0.5 Hz and 10 Hz respectively.

c. Excitation point of application of seismic input

Bottom end of the bushing pocket

NOTE: Two cycles of resonant sinusoidal with 0.3 G or actual earthquake motion may be used if necessary as input wave on the ground surface other than the above design earthquake force.

(2) Transformer

0.5 G Static horizontal acceleration

2.4 Earthquake-resistant design of indoor porcelain-clad equipment and transformers

2.4.1 Types of facility

Transformers, switchgears, current transformers and cable heads to be placed indoor including basements and roofs.

2.4.2 Basement and ground floor

Design method and earthquake force are the same as articles **2.2** and **2.3**.

2.4.3 Second floor and above

Specific disign should be made considering the seismic response of the building.

2.5 Earthquake-resistant design of other facility

2.5.1 Types of facility

Auxiliary power generators, switch boards, compressors, and so on. Although cables for transmission, operational cables and pressurized pipes are not required to design under earthquake force, special attention must be paid in design and construction so that they have never been ruptured during an earthquake. The buses, which are essentially designed based on mechanical factors, have never experience seismic damage. Thus, they are expected to have sufficient strength for an earthquake force.

2.5.2 Design method

Static force design method should be applied.

2.5.3 Seismic input

(1) Auxiliary power generators (excluding internal combustion generation equipment)

0.5 G Static horizontal acceleration
(for those installed on the first floor and below)

NOTE: The earthquake force for the combustion power generator equipment is found in "PRELIMINARY GUIDELINES FOR EARTHQUAKE RESISTANT DESIGN OF INDEPENDENT POWER GENERATOR (JAPANESE SOCIETY OF INTERNAL COMBUSTION POWER GENERATOR)".

(2) Switchboards

1.5 G Static horizontal acceleration
(for those installed on the third floor and below)

(3) Compressors

0.5 G Static horizontal acceleration
(for those installed on the first floor and below)

3. TRANSMISSION STEEL TOWERS

As transmission steel towers which were designed by considering wind effects have been thought to adequately withstand seismic effects, earthquake resistant considerations of them have been generally omitted. In other words, from the fact that no failure of the structural members due to seismic shaking have been observed, it has been considered that transmission steel towers were adequately safe except that there were some damages caused by ground deformations such as settlement, rising, collapses, and cracks of the ground.

Therefore, seismic force is not prescribed in the design code JBC-127-1979. Seismic force is, however, possibly to exceed wind effect for particular types of structures. In this case, earthquake resistant design is provided by Seismic coefficient method as matters now stand, and seismic coefficient which is used in seismic coefficient method is determined based on the detailed regulations of the Earthquake Resistant Regulations for Building Structures and Notification No. 1074 of the Ministry of Construction. The method to determine the seismic force is described as follows.

Seismic coefficient, which is the ratio of the maximum acceleration of earthquake to the acceleration of gravity is determined as

$$K=\frac{a}{g} \qquad \ldots.(3.1)$$

and inertia force F which acts on structures is given by the following equation.

$$F=\frac{W\cdot a}{g}=K\cdot W \qquad \ldots.(3.2)$$

Seismic coefficient method is the design method with $K\cdot W$ in the above equation acting statically on the center of gravity of the structure.

Table 3.1 presents the standard values of seismic coefficients.

Table 3.1 **Standard seismic coefficient**

Application	Standard seismic coefficient (K_0)
Lower 16 m in height	0.2
Over 16 m in height	Add 0.01 to 0.2 in every 4 m
Wooden structures standing on very poor ground area	0.3
Water tank sticking out from a roof chimney	0.3

Notification No. 1074 of the Ministry of Construction, on the other hand, prescribes that K_0 can be reduced to the values given by the following equation by using α which is shown in Table 3.3 when the ground type comes under Table 3.2, and by using the reducing coefficient β when the ground type comes under the particular area which is provided separately.

$$K = K_0 \cdot \alpha \cdot \beta$$

But if the value of $\alpha \cdot \beta$ becomes less than 0.5, it is set at $\alpha \cdot \beta = 0.5$. The very poor ground area which is shown in **Table 3.1** comes under either (1) or (2) of the following ground classification.

(1) An alluvium (including banking) which is formed by hums, mud soil, or other some kinds of materials and is more than 30 m in thickness.

(2) Reclaimed land from marsh or sea, which is formed by trash, mud soil or other same kind of materials, and is about more than 30 m in thickness with the younger condition less than about 30 years since the land was reclaimed.

Table 3.2 **Classification of ground**

Classification	Ground profile
The first class	Ground which very widely consists of mainly sedimentary layers former the Tertiary such as bedrock, gravel layer, sandy stiff clay or other layeres.
The second class	Ground surrounding a structure, which widely consists of mainly a diluvium such as gravel layer, sandy stiff clay, loam or other layeres or gravel/sandy layeres with about 5 m in thickness or more.

Table 3.3 **Correction factor, α, for standard K_0**

Classification of structure types whose parts are affected by horizontal seismic coefficient Classificantion of ground	Wood	Steel	Reinforced concrete, steel frame-reinforced concrete or steel frame concrete
The first class	0.6	0.6	0.8
The second class	0.8	0.8	0.7

The design seismic coefficients based on the Building Standards are shown above. Moreover, there are other seismic standards such as the tentative design seismic coefficient based on the committee of seismic structure design in JSCE and the Earthquake Resistant Design Specifications of Highway Bridges by Japan Road Association in which earthquake resistant design method based on seismic coefficient method is also shown. It is necessary to refer these standards and to make a comprehensive judgement. Since the seismic force specified in this section will be revised and recent researches to evaluate earthquake resistant designs through a dynamic analysis are being promoted in other institutions, it is necessary to take account for the results of those researches according to circumstances.

4. TUNNELS FOR POWER TRANSMISSION

4.1 General

(1) Seismic calculation should be, in principal, performed by the seismic deformation method.

(2) It is desirable to perform dynamic analysis for particular portions such as a connection between a tunnel and a shaft, varied ground conditions, etc.

4.2 Earthquake effects

(1) Special ground deformation should be considered as earthquake effects when seismic design for longitudinal direction of a tunnel is performed.

(2) Ground deformation with depth, shear force around a tunnel and inertia force of a tunnel should be considered as earthquake effects when seismic design for transverse direction of a tunnel is performed.

4.3 Seismic calculation method

4.3.1 Calculation of ground deformation

(1) Horizontal ground deformation at a depth of X (m) from the ground surface should be determined by Eq. (4.1) in the seismic deformation method.

$$U_h(x)=\frac{2}{\pi^2}S_v\cdot T\cdot K_h'\cdot\cos\frac{\pi x}{2H} \qquad \ldots.(4.1)$$

Where,

$U_h(x)$: Ground deformation at a depth of X (m) from the ground surface, (cm)

S_v: Response velocity per unit ($K_h'=1.0$) seismic coefficient, (cm/s)

T: Natural period of surface ground, (s)

K_h': Design basis horizontal seismic coefficient specified at the seismic bed layer.

H: Thickness of a surface layer, (m)

(2) Response velocity S_v per unit seismic coefficient should be calculated using Fig. 4.1 in accordance with a natural period derived from Eq. (4.2).

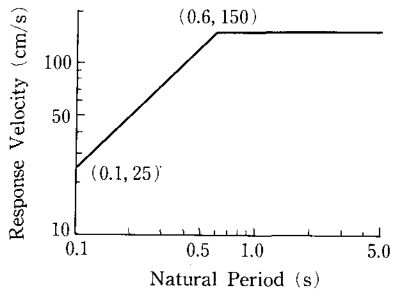


Fig. 4.1 Response velocity per unit seismic coefficient

(3) Natural period of a surface layer should be determined by Eq. (4.2) taking non-linear behavior of the ground into account.

$$T=\frac{4H}{V_s} \qquad \ldots\ldots(4.2)$$

Where,

T: Natural period of a surface layer, (s)
H: Thickness of a surface layer, (m)
V_s: Average shear wave velocity at shear strain level of 10^{-3}, (m/s)

i) Thickness of a surface layer H is determined as a distance from the seismic bed layer to the ground surface.

ii) Shear wave velocity V_s should be determined as the strain level of 10^{-3} based on the observed data in principal. They may be estimated through N-value also. Determination methods of V_s are presented in Table 4.1.

Table 4.1 Shear wave velocity V_s at 10^{-3} strain level of the ground

<table>
<tr><th>Method</th><th>V_s (m/s)</th><th>Note</th></tr>
<tr><td>In-situ observation (PS logging, etc.)</td><td>$V_s=CV_{s0}$
V_{s0}: Observed shear wave velocity (m/s)
C: Correction factor
<table>
<tr><th></th><th>Alluvial</th><th>Pleistocene</th></tr>
<tr><td>Sand</td><td colspan="2">0.6</td></tr>
<tr><td>Clay</td><td>0.85</td><td>0.75</td></tr>
</table>
</td><td></td></tr>
<tr><td>Estimation from N-value</td><td>
<table>
<tr><th></th><th>Alluvial</th><th>Pleistocene</th></tr>
<tr><td>Sand</td><td>$61.8N^{0.211}$</td><td>$123N^{0.125}$</td></tr>
<tr><td>Clay</td><td>$122N^{0.0777}$</td><td>$129N^{0.188}$</td></tr>
</table>
</td><td>Minimum V_s may be set at 40 m/s</td></tr>
</table>

(4) Design basis horizontal seismic coefficient K_h' specified at the seismic bed layer is determined by Eq. (4.3).

$$K_h'=0.15 \qquad \text{....(4.3)}$$

4.3.2 Sectional forces of a tunnel for longitudinal direction

(1) Calculation of sectional forces

Sectional forces of a tunnel for longitudinal direction are calculated by Eq. (4.4).

$$\left.\begin{aligned}
P_h &= \alpha_1 \frac{\pi E_A}{L} U_h \\
\overline{P_h} &= \overline{\alpha_1} \frac{2\pi E_A}{L} U_h \\
M_h &= \alpha_2 \frac{4\pi^2 E_{Ih}}{L^2} U_h \\
\overline{M_h} &= \overline{\alpha_2} \frac{\sqrt{2}\,\pi^2 E_{Ih}}{L^2} U_h \\
Q_h &= \alpha_2 \frac{8\pi^3 E_{Ih}}{L^3} U_h \\
\overline{Q_h} &= \overline{\alpha_2} \frac{2\pi^3 E_{Ih}}{L^3} U_h
\end{aligned}\right\} \qquad \text{....(4.4)}$$

Where,

P_h, $\overline{P_h}$: Axial force caused by the seismic wave on horizontal plane, (kgf)

M_h, $\overline{M_h}$: Bending moment caused by the seismic wave on horizontal plane, (kgf-cm)

Q_h, $\overline{Q_h}$: Shear force caused by the seismic wave on horizontal plane, (kgf)

E_A: Axial rigidity, (kgf)

E_{Ih}: Bending rigidity in horizontal plane, (kgf-cm^2)

U_h: Horizontal ground deformation at the neutral axis of a tunnel, (cm)

L: Apparent wave length of the seismic wave, (cm)

α_1, $\overline{\alpha_1}$: Strain transmitting coefficient from the ground to a tunnel in longitudinal direction caused by the seismic waves on horizontal plane, and determined by Eq. (4.5) and Eq. (4.7)

α_2, $\overline{\alpha_2}$: Strain transmitting coefficient from the ground to a tunnel in horizontal plane caused by the seismic waves on horizontal plane, and determined by Eq. (4.6) and Eq. (4.7)

Seismic waves on horizontal plane consist of sinusoidal waves with particle motions perpendicular (refer to P_h, M_h, Q_h, α_1, α_2) and parallel (refer to $\overline{P_h}$, $\overline{M_h}$, Q_h, $\overline{\alpha_1}$, $\overline{\alpha_2}$) to their propagating direction.

$$\left.\begin{aligned}
\alpha_1 &= \frac{1}{1+\left(\dfrac{2\pi}{\lambda_1 L'}\right)^2} \\
\overline{\alpha_1} &= \frac{1}{1+\left(\dfrac{2\pi}{\lambda_1 L}\right)^2}
\end{aligned}\right\} \qquad \text{....(4.5)}$$

$$\left.\begin{aligned}\alpha_2&=\frac{1}{1+\left(\frac{2\pi}{\lambda_2 L}\right)^4}\\ \bar{\alpha}_2&=\frac{1}{1+\left(\frac{2\pi}{\lambda_2 L'}\right)^4}\end{aligned}\right\}\qquad\ldots.(4.6)$$

Where,

$$\left.\begin{aligned}\lambda_1&=\sqrt{\frac{K_{g1}}{E_A}}\quad(1/\mathrm{cm})\\ \lambda_2&=\sqrt[4]{\frac{K_{g2}}{E_{Ih}}}\quad(1/\mathrm{cm})\\ L'&=\sqrt{2}\,L\end{aligned}\right\}\qquad\ldots.(4.7)$$

K_{g1}: Ground spring coefficient for longitudinal direction, (kgf/cm^2)
K_{g2}: Ground spring coefficient for transverse direction, (kgf/cm^2)

(2) Rigidity of the structure

Adequate rigidity should be evaluated for a tunnel. Uniform rigidity can be used both for the compression and the tension in the case of a box culvert. In the case of a shield tunnel, expansion at a segment joint can be considered by evaluating deformation of the bolts and the plates of a joint.

(3) Ground spring coefficient

Ground spring coefficients are determined by Eq. (4.8) for seismic calculation of a tunnel.

$$\left.\begin{aligned}K_{g1}&=k_{g1}G_s\\ K_{g2}&=k_{g2}G_s\end{aligned}\right\}\qquad\ldots.(4.8)$$

Where,

k_{g1}, k_{g2}: Constants for ground spring coefficients, K_{g1}, K_{g2}.
G_s: Shear modulus (kgf/cm^2) of the ground near a tunnel determined by Eq. (4.9).

$$G_s=\frac{\gamma_t}{g}V_s^2\qquad\ldots.(4.9)$$

γ_t: Unit weight of a soil (kgf/cm^2)
g: Gravity acceleration (980 cm/s^2)
V_s: Shear wave velocity of the ground near a tunnel.

(4) Wave length

Apparent wave length along the ground surface is determined by Eq. (4.10).

$$L=VT\qquad\ldots.(4.10)$$

where,

L: Apparent wave length along ground surface (m)
V: Apparent wave velocity of a seismic motion (m/s)
T: Natural period of a surface layer (s)

Apparent wave velocity of a seismic motion is determined by Fig. 4.2.

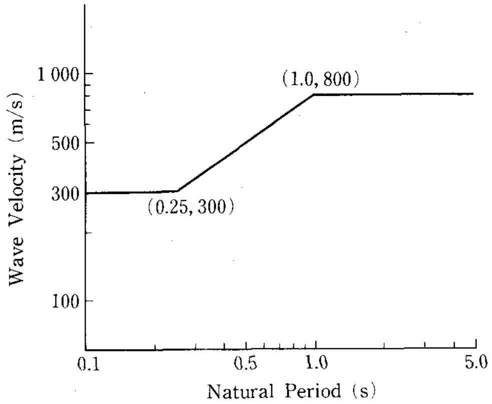


Fig. 4.2 Apparent wave velocity

(5) Superimposing of sectional forces

Seismic capacity of a tunnel may be evaluated through adequate superimposing of sectional forces, if necessary, taking into account relationship of phase lag of various seismic waves propagating in a surface layer complicatedly.

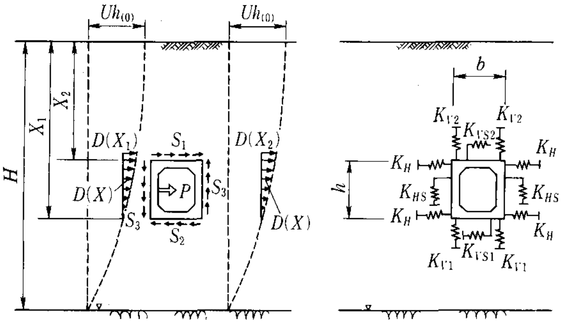
(6) Flexible joints and relative displacement at the joint

Sectional forces determined by Eq. (4.4) are corrected when flexible joints are employed taking into account the effect of the joint on sectional forces. It is necessary to check relative displacement at the joint to maintain its performance.

4.3.3 Sectional forces of a tunnel for transverse direction

(1) Calculation of sectional forces

Sectional forces are determined by a method shown in Fig. 4.3 in the case of a tunnel with rectangular cross section. It is necessary to superimpose seismic sectional forces and ordinary sectional forces because the seismic forces shown in Fig. 4.1 are increment during an earthquake.



(a) Earthquake Effects (b) Soil Springs

Fig. 4.3 Seismic calculation method of the transverse direction for a rectangular tunnel section

Where,

$D(x)$: Relative displacement of ground to the lower slab of a tunnel
$D(x_2)$: Horizontal ground displacement at the upper slab of a tunnel
S_1: Seismic shear force acting on the upper slab of a tunnel
S_2: Seismic shear force acting on the lower slab of a tunnel
S_3: Seismic shear force acting on the side walls of a tunnel
P: Inertia force of a tunnel
K_H: Normal ground spring at the side walls of a tunnel
K_{HS}: Shearing ground spring at the side walls of a tunnel
K_{V1}: Normal ground spring at the lower slab of a tunnel
K_{VS1}: Shearing ground spring at the lower slab of a tunnel
K_{V2}: Normal ground spring at the upper slab of a tunnel
K_{VS2}: Shearing ground spring at the upper slab of a tunnel

(2) Seismic shear forces around a tunnel

Seismic shear forces around a tunnel may be determined by Eq. (4.11).

$$\left.\begin{aligned} S_1 &= \frac{G_s}{100\pi H} S_v \cdot T \cdot K_h' \sin\frac{\pi x_2}{2H} \\ S_2 &= \frac{G_s}{100\pi H} S_v \cdot T \cdot K_h' \sin\frac{\pi x_1}{2H} \\ S_3 &= \frac{1}{2}(S_1 + S_2) \end{aligned}\right\} \quad \ldots .(4.11)$$

Where,

S_1: Shear force acting on the upper slab of a tunnel, (kgf/cm^2)
S_2: Shear force acting on the lower slab of a tunnel, (kgf/cm^2)
S_3: Shear force acting on the side walls of a tunnel, (kgf/cm^2)
S_v: Response velocity per unit seismic coefficient as shown in Fig. 4.1, (cm/s)
T: Natural period of a surface layer determined by Eq. (4.2), (s)
K_h': Design basis horizontal seismic coefficient determined by Eq. (4.3)
G_s: Shear modulus (kgf/cm^2) of the ground near a tunnel determined by Eq. (4.9).
X_2: Depth from the ground surface to the upper slab of a tunnel, (m)

(3) Displacement of the ground relative to a tunnel

Displacement of the ground relative to a tunnel may be determined from Eq. (4.1)∼Eq. (4.12).

$$D(x) = U_h(x) - U_h(x_1) \quad \ldots .(4.12)$$

Where,

$D(x)$: Ground displacement (cm) relative to the lower slab of a tunnel at a depth of X(m)
X_1: Depth(m) from the ground surface to the lower slab of a tunnel

(4) Inertia force of a tunnel

Inertia force of a tunnel may be determined by Eq. (4.13).

$$P = WK_h \qquad \ldots\ldots(4.13)$$

Where,

P: Inertia force of a tunnel, (kgf/cm²)
W: Unit weight of a tunnel, (kgf/cm²)
K_h: Design basis horizontal seismic coefficient

(5) Reactive coefficient of the ground

Reactive coefficient of the ground may be determined by Eq. (4.14).

$$\left.\begin{aligned} K_H &= 3\frac{Gs}{h} \\ K_{HS} &= \frac{Gs}{h} \\ K_V &= 3\frac{Gs}{b} \\ K_{VS} &= \frac{Gs}{b} \end{aligned}\right\} \qquad \ldots\ldots(4.14)$$

Where,

K_H: Reactive coefficient at the side walls of a tunnel, (kgf/cm³)
K_{HS}: Shear spring constant at the side wall of a tunnel, (kgf/cm³)
K_V: Reactive coefficient at the lower slab of a tunnel, (kgf/cm³)
K_{VS}: Shear spring constant at the lower slab of a tunnel, (kgf/cm³)
h: Height of a tunnel section, (cm)
b: Width of a tunnel section, (cm)

4.4 Evaluation of safety

4.4.1 General

Safety of a tunnel during an earthquake should be evaluated by the stress of the structure members and the displacement at the joints.

4.4.2 Allowable stress

Allowable stresses of the concrete and the re-bars for the seismic design are, in principal, set at 1.5 times of the ordinary allowable stresses specified in the Standard Specification of Concrete, JSCE.

Allowable stresses of shield segments are set at 1.5 times of ordinary allowable stresses specified in the Standard Segment for Shield Construction, Japan Sewerage Association.

4.4.3 Allowable displacement at the joint

Allowable displacement at the joint should be set based on the deformation capacity considering the mechanism of the joint and water proof.

5. CONCLUDING REMARKS

Earthquake resistant design methods are outlined for the substation facilities, transmission towers and tunnels.

Reliability of an electric power system is improved through those specific design. Moreover, the system has been provided against the accident with redundant systems such as double loop transmission lines and backup computers. Emergency switching operation will be also performed in case of failure of electric equipment in order to avoid successive functional failure.

Further study is needed to optimize the earthquake resistant design and the restoration strategy.