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# Pile-in-Tube Foundations with Reserve Switch-off Elements and Other Systems for Seismic Response Adaptive Control

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# PILE-IN-TUBE FOUNDATIONS WITH RESERVE SWITCH-OFF ELEMENTS AND OTHER SYSTEMS FOR SEISMIC RESPONSE ADAPTIVE CONTROL

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ABSTRACT

Predominant ground motion frequencies and spectra could differ sufficiently at different earthquakes on one site. The reasons of the differences are the epicenter distance, the focal depth, and many others.

As it is well known, the frequency spectral configuration and predominant frequency values influence the structural seismic response and seismic behavior of structures (Mexico earthquakes 1957, 1962; Bucharest, 1977, Spitak, Armenia, 1988 and other). The maximum seismic response depends of how close the fundamental frequency values of the structure are to the predominant ground motion frequencies. Seismoisolation as an effective approach to seismic response control became popular recent decades in many countries.

The conclusions of RCEE analytical and experimental studies are that in abovementioned cases when different spectra and predominant frequencies could be expected at a given site structures with changing (self-adjusting) natural frequencies could be effective for adaptive seismic response control.

Several dozens of structures with switch-off reserve elements are designed with RCEE participation and constructed in Siberia, in Caucasus, near Lake Baykal and at other earthquake dangerous areas of Russian Federation.

Besides, of pile-in-tube foundations also other structural systems are constructed. Among these systems are rocking supports with reserve switch-off elements, flexible columns with switch-off reserve rigid elements,pile-in-tube, sliding supports and others.

## INTRODUCTION

As far back as in the 60s a concept of seismoisolation with re-adjustable (self-adjustable) dynamic characteristics was formulated [Eisenberg, 1965, 1971]. The recent years a comprehensive program of theoretical and experimental studies has been executed, the structural systems of adaptive seismoisolation, including foundation ones, have been developed [Eisenberg, 1976, 1988a, 1988b, Rakhimov, 1989, Albert, 1986].

Predictions of dominant periods, amplitude-frequency responses, ground motion duration and intensity are uncertain and incomplete in principle.

The earthquake instrumental records have demonstrated considerable variety of ground vibration dominant periods and spectrum modes. Sometimes this diversity is governed by ground conditions, e.g. the low-frequency spectrum is determined to a considerable extent by thick loose ground layers in Mexico City [Eisenberg, 1976]. However, in other cases close earthquake detection station even on the bedrock base record different ground motions [Eisenberg, 1990].

MATHEMATICAL MODEL OF GROUND SEISMIC MOTIONS

A mathematical model of ground seismic motions taking into account possible, physically realizable diversity of spectral distribution for different earthquakes that allow predicting spectra of probable but non-recorded earthquakes was offered.[Eisenberg, 1971, 1976]

A feature of this design model is that the spectral density $S(\omega,\overline{\omega})$ of the stochastic process is a function of two variables – frequency $\omega$ and dominant (carrier) frequency $\overline{\omega}_j$, i.e. this model is an element of a set of processes, and in design of structures one has to consider all these elements.

Let us present the mathematical model of the seismic ground motion as a non-steady Gaussian multiplicative process

$$\Phi(t,\omega,\overline{\omega}_j) = A(t,\overline{\omega}_j)\cdot\varphi(t,\omega,\overline{\omega}_j) \tag{1}$$

in the range of

$$\overline{\omega}_{\min} \le \overline{\omega}_j \le \overline{\omega}_{\max},$$

where $A(t,\overline{\omega}_j)$ – envelope function normalized so that $\max\left|A(t,\overline{\omega}_j)\right| = 1$;

$\overline{\omega}_j$ – the process dominant frequency, the boundary values of which $\overline{\omega}_{\min}$ and $\overline{\omega}_{\max}$ are assumed on the basis of available empirical data.

Envelope $A(t,\overline{\omega}_j)$ is assumed at fixed values $\overline{\omega}_j$ in the form of

$$A(t,\overline{\omega}_j) = A_0\cdot t\cdot e^{-\varepsilon_0 t} \tag{2}$$

Properly speaking $\varepsilon_0$ is a random value. Considering the known stability of value $\varepsilon_0/\overline{\omega}_j$, the mean value $\varepsilon_0/\overline{\omega}_j$ = const is assumed for the design model.

$\varphi(t,\omega,\overline{\omega}_j)$ – steady-flow Gaussian process;

Random function $\varphi(t,\omega,\overline{\omega}_j)$ can be written as

$$\varphi(t,\omega,\overline{\omega}) = \sigma(\overline{\omega}_j)\cdot\overline{\varphi}(t,\omega,\overline{\omega}_j) \tag{3}$$

where $\sigma(\overline{\omega}_j)$ – standard of process $\varphi(t,\omega,\overline{\omega}_j)$;

$\overline{\varphi}(t,\omega,\overline{\omega}_j)$ – normalized random function, the dispersion of which is presented as

$$\overline{\sigma}^2\left(\overline{\omega}_j\right) = \int_{-\infty}^{+\infty} S(\omega,\overline{\omega}_j)\,d\omega = 1 \tag{4}$$

In papers [Eisenberg, 1971, 1976] parameters $A_0$, $\overline{\sigma}^2$ and $\alpha$, characterizing the assumed model, are determined as functions of the dominant frequency $\overline{\omega}_j$. By substituting these parameters into (1), we obtain

$$\Phi\left(t,\omega,\overline{\omega}_j\right) = \frac{\overline{\omega}_j t}{20\pi}\exp\left(1-\frac{\overline{\omega}_j t}{20\pi}\right)\cdot\overline{\varphi}(t,\omega,\overline{\omega}_j) \tag{5}$$

According to the assumed definition the structural reliability analysis is implemented by linear search of all $\Phi(t,\omega,\overline{\omega}_j)$ elements of set $\mathrm{M}_{\Phi j}$ and location of the most hazardous one for this system to be considered in design of the system's bearing capacity. Papers [Eisenberg, 1971, 1976] offered the methods of generating earthquake pseudo-accelerograms in the form of determinate presentations of stochastic processes.

OPTIMUM STRUCTURAL DESIGN PROBLEM

Basing on solution of the optimum structural design problem under seismic loads with the above-described mathematical model, it is shown that the optimum seismic protection system belongs to the class of adaptive systems. The term "optimality" is conceived here in the narrow sense of the minimum seismic load.

For each fixed combination of structural parameters the maximum load is found, i.e. the most hazardous action, by direct enumeration of all elements of the set comprised by the mathematical model. Then a combination of the system's parameters providing a minimum of all specified maxima is found. If as a criterion of optimality the inertial seismic force is assumed, then the seismic displacement limitations are taken into account. In the recent years as a result of numerous studies it has become evident that in the general case under uncertainty of predicting future earthquake parameters the seismic isolation is particularly effective under combination of the following three elements [Eisenberg, 1976, 1988a, 1988b, Rakhimov, 1989, Albert, 1986, Yaremenko,1988, Kurzanov, 1991, Aubakirov, 1988]:

1) high slenderness ratio of the structure or (being the same) low rigidity in the limit state when the redundant braces are disengaged;
2) high initial rigidity of redundant elements or redundant defense lines as they are called sometimes;

3) higher energy absorption, dissipation of seismic vibration energy or, in other words, damping.

Some systems of adaptive seismoisolation also comprise the fourth element (Fig.1): rigid and sometimes energy-absorbing foundation buffer-blocks – limiters of extremely high horizontal displacements being hazardous from the viewpoint of collapse of the whole building [Eisenberg, 1976, Rakhimov, 1989].

A relatively high slenderness of the system without redundant rigid elements (before their engagement or after their disengagement) is achieved by using slender (reinforced concrete and metal) supports or a framework in the building's lower one or two stories, and sometimes in the basement. In some seismological situations the slender piles in tubes (with air-gaps) are highly advisable.

Another method of achieving a higher finite slenderness is the use of swing (rocking) bearings like tumbler toys. These are ellipsoids [Yaremenko, 1988, Nazin, 1974], swing columns [Yaremenko, 1988, Kurzanov, 1991, Nazin, 1974], swing cap-down mushroom-shaped supports [Cherepinsky, 1973]. Sometimes these supports are called kinematical ones, while the isolation system is called a gravity system, since the gravitational force (gravitation) returns these supports into the initial vertical position.

Rigidity of redundant elements and damping are ensured either by concrete and masonry shear walls, which fail inelastically, or by inelastic engaging steel or other braces between shear walls (e.g. bolts, rivets, rings) or by dry friction of couples "concrete-concrete" [Yaremenko, 1988, Nazin, 1974], "sand-beton" [Nazin, 1974], "teflon-steel" [Polyakov, 1984], etc.

## SEISMOISOLATION SYSTEM "PILE-IN-TUBE"

The "pile-in-tube" seismoisolation system is a combination of the "pile-in-tube" support and inelastic disengaging braces (Fig.2). In some seismological and engineering situations the system may turn to be highly effective. Its design comprises end-bearing piles fully taking up the structure's dead load and other vertical loads; tubes of a relatively large diameter and inelastic disengaging braces, which prior to disengagement tie the tubes and the superstructure. The gap between a pile and a tube may be 10-15 cm with regard to geometric dimensions of piles and foundations.

From the standpoint of seismic load reduction one may point out a few specific effects of the "pile-in-tube" support. One effect is governed by the pile slenderness causing relatively high wave periods of the system. When using plot $\beta$ from the Seismic Code [SNiP II-7-81], for average soils the seismic loads can be reduced three times and more.

Another effect is connected with the fact that the foundation is supported not near the surface, but at a certain depth approximately equal to the pile length. It is known that the seismic acceleration amplitudes diminish with depth, sometimes considerably. Seismicity of loose ground sites resting on bedrock rises in some cases up to 1 point [Chernov, 1985], i.e. in conformance with the current seismic scale the seismic accelerations on the surface can double those on the underlying bedrock. Thus, as a result of "separation" of the pile from the surrounding soil and depth supporting the seismic load can be significantly reduced.

The both abovementioned effects jointly reduce seismic loads. However, due to considerable slenderness of the system the large horizontal displacements of the pile tops may appear. A chain of inelastic disengaging elements is provided to reduce these displacements and to prevent possible displacements of the structure under wind loads and frequent weak earthquakes.

## COMPARISON OF SEISMOISOLATION SYSTEMS

The comparison of various seismoisolation systems most widely used at present in the former USSR countries:

1. Seismoisolation system "With slender supports in lower parts and disengaging inelastic braces"
   System advantages are:
   - the cost of a structure is reduced by 10-12%;
   - the seismic loads – by 2-4 times.

   Limitations in the system use:
   - a certain support height is required (usually at least 2-5 m);
   - in the "pile-in-tube" case it is achieved automatically, in other cases a framed or post-supported basement or ground floor are needed.

2. Seismoisolation system "With kinematical (swing) supports"

   System advantages are:
   - a possibility of wide height control for kinematical supports by varying support geometries.

   Limitations in the system use:
   - relative difficulty of manufacturing the swing posts and the support system as a whole;
   - when the system special damping is not provided, they can be used at 7-8 point design seismicity.

3. Seismoisolation system "With sliding foundation bearers on the basis of the sliding "steel-teflon" couple"
   System advantages are:
   - all storeys can be made from homogeneous components (large-panel walls, brick walls, etc.).

   Limitations in the system use:
   - scarce materials – stainless steel, teflon – are needed;
   - at heavy earthquakes the extreme horizontal displacements may emerge. Therefore the system

can be reliably used in buildings with 8-point design seismicity.

## DATA ON SEISMOISOLATION SYSTEMS USED IN ALREADY BUILT STRUCTURES

More than 180 existing buildings designed seismicity 7-9 point (4-10-storey buildings with load-bearing walls – large-panel, block, brick, cast-in-place, reinforced concrete) were updated since 1961 until 1990:

Seismoisolation system “Pendulum suspension with steel springs” was used by F.D. Zelenkov in 1959 [Zelenkov, 1961].

Seismoisolation system “Slender concrete supports (columns) of the ground floor or basement plus a set of inelastic buffers-displacement limiters: pile-in-tube foundations plus inelastic disengaging braces” was used by TsNIISK et al. on the 91 buildings in 1972-1990 [Eisenberg, 1976, 1988a, 1988b, 1991, Rakhimov, 1989].

Seismoisolation system “Sliding friction supports (Teflon – stainless steel couple) plus buffers-displacement limiters” was used by EERC, TsNIISK and Frunze Polytechnical Institute on the 25 buildings in 1984-1990 [Polyakov, 1984].

Seismoisolation system “Swing concrete supports (kinematical supports) with spherical ends plus engaging braces with dry friction” was used by EERC, TsNIISK and Sevastopolstroy on the 3 buildings in 1972-1974 [Eisenberg, 1976, Nazin, 1974, Yaremenko, 1988].

Seismoisolation system “Swing concrete supports (kinematical supports) of the cap-down mushroom type” was used by KazpromstroyNIIproyekt, TsNIISK et al. on the 55 buildings in 1979-1989 [Cherepinsky, 1973].

Seismoisolation system “Concrete columns with flat ends, inclined buffers-displacement limiters plus dry friction (kinematical supports)” was used by KazpromstroyNIIproyekt, TsNIISK et al. on the 4 buildings in 1987-1990 [Cherepinsky, 1973].

Seismoisolation system “Metal-rubber multi-layer bearers (sandwiches)” was used by TsNIISK in 1985.

## CONCLUSIONS

1. In the recent decades the efficient seismoisolation systems have been developed and being universal enough to be used in seismic hazardous areas under uncertain predictions of seismic load parameters.
2. When using seismoisolation, one should take into account not only the inertial forces, but also displacements of a structure; therefore in design one should consider displacement limitations.
3. The optimum systems of adaptive seismoisolation comprise three basic elements: considerable slenderness in the limit state, high initial rigidity and considerable energy absorption; in some systems the buffer blocks limiting horizontal displacements are used.

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