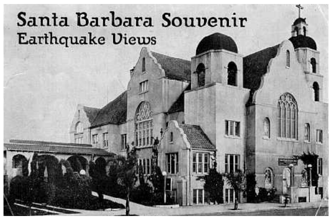

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GROUND DISPLACEMENTS ON SOFT SOIL SITES AND THEIR IMPORTANCE IN SEISMIC DESIGN

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ABSTRACT

Peak ground acceleration, velocity, and displacement values calculated from strong motion records obtained from our seismic instruments, located on soft soil sites, were evaluated as part of our investigation. The purpose of our investigation was to quantitatively demonstrate that in the design of long-period structures on soft soils, the ground displacement factor should be an important consideration. Data from microseismic activities, as well as the motions from the 1988 Spitak earthquake were evaluated and the displacements for various site classes defined by the Building Seismic Safety Council (BSSC) were computed. It was observed that while recorded accelerations increase from Site Class B rock to Site Class E soft soils at anticipated factors, the displacement increase factor between the same Site Classes increases by a much larger amount. While current building design according seismic codes are based on acceleration values for different site class, it is recommended that for long-period structures, design parameters include peak ground displacements. The implication of using ground displacement in foundation design and seismic separation of adjacent building foundations are also discussed.

INTRODUCTION

Upon the conclusion of macroseismic inspections of buildings in zones of strong earthquakes, it is noted that damages and destruction of buildings , are generally caused by incremental relative displacements of their constitutive parts. Typically, such damages take place in the buildings and in the structures located on soft soil strata.

Influence of a ground conditions on intensity of seismic impacts is well-known and is considered in standards of anti-seismic construction design of all countries [7, 8, 9, 10]. As a general rule, earthquake loads on structures are dependent on ground acceleration and the influence of site conditions, for which corresponding design coefficients are used.

This factor used within the Seismic Code of Russian Federation (Construction in seismic areas) [10] may increase or decrease the seismicity by one point (on the MSK64 scale) is considered. In the building codes of USA *(BSSC)* [7, 9] the site class coefficients F_a and F_v are site dependent factors. These and other factors in different countries are used in determining a realistic seismic impacts on structures, by adjustment of the design accelerations. These approaches give a positive results in dense ground conditions (site categories *A, B, and C*).

However, unlike greater structure displacements caused by soft soils, seismic accelerations occur on different sites within a certain range. Therefore, application of the above-mentioned factors leads to some correction of design accelerations, but does not consider the impact of possible greater displacement resulting from soft soils.

For example, Figure 1a shows, for the range of shear wave velocities used, the 5% damped acceleration response spectra of the calculated ground surface motions and the input rock motion for the site in Gyumri (previously Leninakan, Armenia) [11]. Figure 1b plots the ratio of spectral acceleration on soft soils (site class E) and bedrocks (site class A) for the short-period spectral acceleration (**$S_S > 0.15g$**), according to *BSSC* [7, 9]. On Fig. 1a an amplification of accelerations due to soft soils of up to 2 times takes place and *BSSC* (fig.1b) envisions a potential increase of up to 3 times. However, as it will be indicated below, displacements on soft soils can increase as much as ten times and by whereas correction of accelerations they cannot be considered.

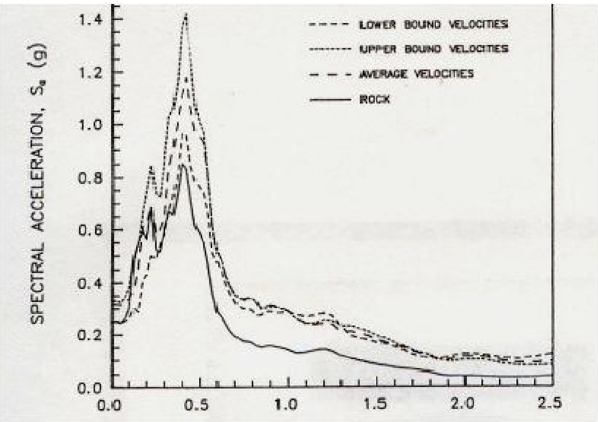

Fig.1a Acceleration response spectra for the rock and soft soils [11]

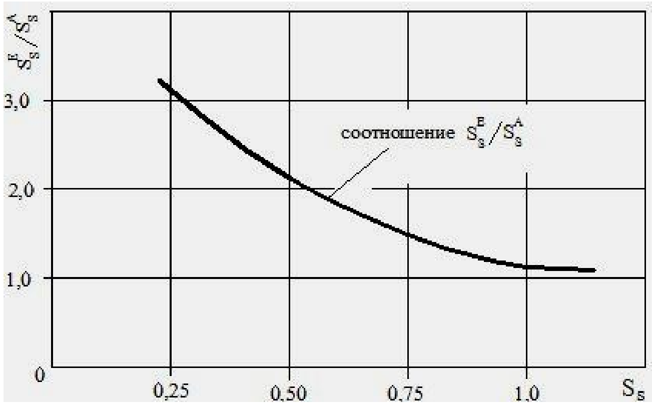

Fig.1b Ratio of spectral acceleration (soft soils/rock) On Site Coeff. F_A, (BSSC)

DISPLACEMENTS ON SOFT SOILS

This study is an attempt of comparative analysis of displacements, velocities and accelerations on soft soils resulting from strong earthquakes. As an initial material, our own database of numerous measured of shear wave velocities and the prevailing (dominant) periods on different sites were used, executed for seismic microzoning. The results of research in the well-studied area of the December-1988 Spitak earthquake by experts from different countries are used also [6, 11, 12..].

The velocities of particles oscillating movement (V) from the density of a stream of earthquake energy (F_o) with the following formula are defined [1]…

$$F_0 = V^2 V_S \rho \tag{1}$$

where V_S is the shear wave velocity, ρ is the density of soils.

The energy generated by the Spitak earthquake with a magnitude of up to 7.0 makes ($E = 10^{22}$ erg $\approx 10^{15}$ N.m). It is connected with density of a stream of energy with following formula:

$$E = \int_S \int_T F_0 dS\, dT \tag{2}$$

For the bounded territory it is accepted $E = F_0\, S\, T$. In the epicentre zone of the Spitak earthquake, at a depth of the seismic center of 10km., for a semicircle surface, it has $S = 2\pi R^2 = 6{,}28 \cdot 10^2 \mathrm{km}^2 = 6{,}28 \cdot 10^8\ \mathrm{m}^2$. Duration of record of the basic impact in near zone is $T = 24$sec. (Recorded at seismic station of Ashotsq). On these data the density of a stream of energy is made out as:

$F_0 = E / S\,T = 1 \cdot 10^{15}$ N.м. / ($6{,}28 \cdot 10^8 \mathrm{m}^2 \cdot 24$ sec) = $663 \cdot 10^2$ N/m.sec.

The portion of the seismic energy, directed on horizontal oscillating movement makes [8].

$\nu = 1/\sqrt{2} \approx 0{,}71$ and $F_0^{\nu} = 663 \cdot 10^2 \cdot 0{,}71$ N/m.sec.= $470{,}7 \cdot 10^2$ N/m.sec.

For superficial, rocky ground, we have average values of $Vs = 2{,}7$ km/sec. and $\rho = 2400$Kg/m3. From (1), for site of the first category (*class A*) the velocity of particles oscillating movement makes…

$V^2 = F_0^{\nu} / V_S\, \rho = 0{,}00726\ \mathrm{m}^2/\mathrm{sec}^2$, $V = 0{,}085$m/sec = 8,5 sm./sec.

The above values approximately corresponds to an earthquake of VII points on the Russian MSK64 scale. The additional increase in intensity of concussions occurs within the limits of friable strata [1, 5, 6, 11,12..]. Here, it is necessary to note that in the city of Vanadzor (previously Kirovakan) the intensity of Spitak earthquake on analogous sites (*class A*) also is estimated as VII points [2, 5, 11].

Is accepted, that the density of seismic energy does not vary in different soils, and velocities of particles' oscillating movement are similarly defined on different sites. For the purpose of a more detailed differentiation of soils with respect to seismic properties, site grading according to *BSSC* (USA) is accepted per Table 1 below:.

Table 1. Average values *Vs* and particles' oscillating movement velocities *V* for various site classes:

Site Class	A	B	C	D	E
BSSC (m/sec)	$V_S > 1500$	$1500 > V_S > 760$	$760 > V_S > 360$	$360 > V_S > 180$	$V_S < 180$
$V_S^{av.}$ (m/sec)	V_S=2700	V_S= 980	V_S= 620	V_S= 210	V_S= 110
ρ (Kg/m^3)	2400	2150	1900	1650	1350
V (sm/sec)	8,5	14,9	20,0	36,9	56,3

The average values of shear waves velocities (on site class), which are received as a result of processing more than 100 measurement on different sites and archival records data, are given in Table 1. Presented here also are the corresponding densities and the calculated values of velocities *V* of particles oscillating movement.

Displacement-*D*, accelerations-*A* and stress -τ on known expressions for seismic motion in the unlimited environment and condition on a surface is defined (3).

$$\frac{\partial^2 D}{\partial t^2} = V_S{}^2 \frac{\partial^2 D}{\partial x^2}; \qquad \tau = V_S{}^2 \rho \frac{\partial D}{\partial x} \tag{3}$$

The function $D = D_0 \sin 2\pi\,(t / T_S - x / L_S)$ which with sufficient accuracy for a task describes seismic motion in the initial, the most intensive, arrival lot of S waves is set.

For velocities, accelerations and stress is accordingly had:

$$\begin{aligned} V &= D_0 (2\pi / T_S) \cos 2\pi (t / T_S - x / L_S) \\ A &= -D_0 (2\pi / T_S)^2 \sin 2\pi (t / T_S - x / L_S) \\ \tau &= -V_S^2 \rho\, D_0 (2\pi / L_S) \cos 2\pi (t / T_S - x / L_S) \end{aligned} \tag{4}$$

Having arrived at the calculated values of velocity *V* for the various sites,, on expressions (4) corresponding maximal displacements, accelerations and stress, on values of the prevailing periods T_0 are determined.

The Calculated displacements, accelerations and stress for average values *To* are given in table 2.

Table 2. Values of displacements, accelerations and stress for various sites.

Site Class	A	B	C	D	E
V (sm/sec)	8,5	14,9	20,0	36,9	56,3
T_0^{av} (sec)	0,13	0,22	0,28	0,49	1,00
D_0 (sm.)	0,17	0,52	0,89	2,88	8,96
A (sm/sec^2)	397	424	448	473	353
τ (kN/m^2)	552	313	235	128	84

Through the results of all available data [5, 6, 11,12..] the curves of relative displacements, velocities and accelerations, depending on a ground conditions (at *Vs*) are plotted in fig.2. The Fig. 2 ordinate shows a ratio of sizes of the given parameter and the corresponding parameter for class B (V_S = 980 m/sec). Here, for comparison, curved lines of relative velocities and accelerations according to site coefficients - *Fv* and *Fa* (*FEMA P-750*) are given.

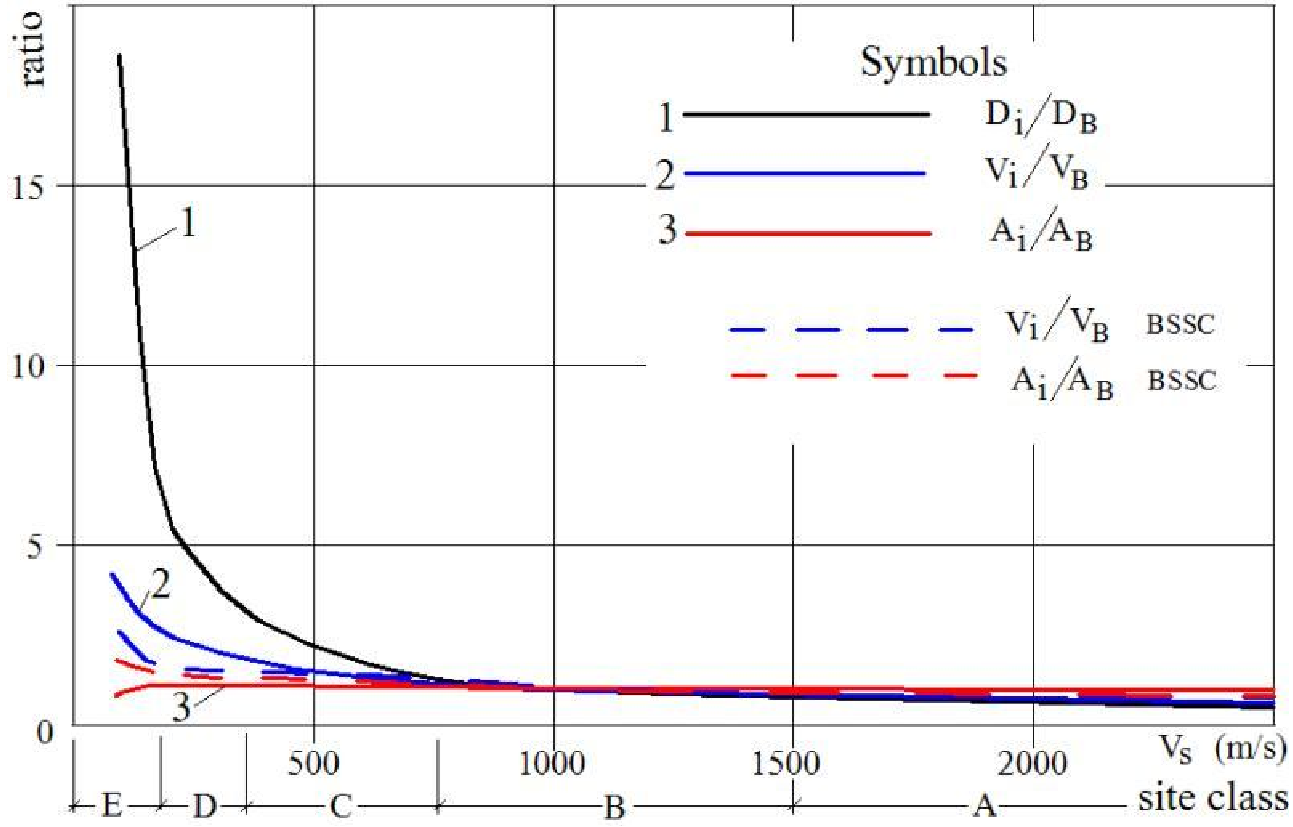

Fig.2. Changes of relative displacements –D_i / D_B, speeds –V_i / V_B, and accelerations –A_i /A_B depending on a soil conditions

According to the calculated results, the change of velocities and accelerations on soft soils basically are coordinated with values in BSSC , but displacements increase significantly more (up to several tens of times). The same results turn out at natural measurements. Fig.3 shows seismograms and accelerograms, recording on stations in Gyumri (Leninakan) (Len, site class E) and Gogaran (Gog, site class B) at aftershock with magnitude 4,7 Spitak earthquakes [6]. These stations are located on the same distance from the epicentre (24 and 23km.) and at practically identical accelerations (accordingly 15 and 18 sm/sec^2) displacements on soft soils are ten times greater than on bedrock of a category B (accordingly 0,25 and 0,024см). Thus, displacement on soft soils increase repeatedly (fig.2, fig.3), whereas accelerations on different sites are changed at a smaller range (fig.1a,b; fig.2; fig.3).

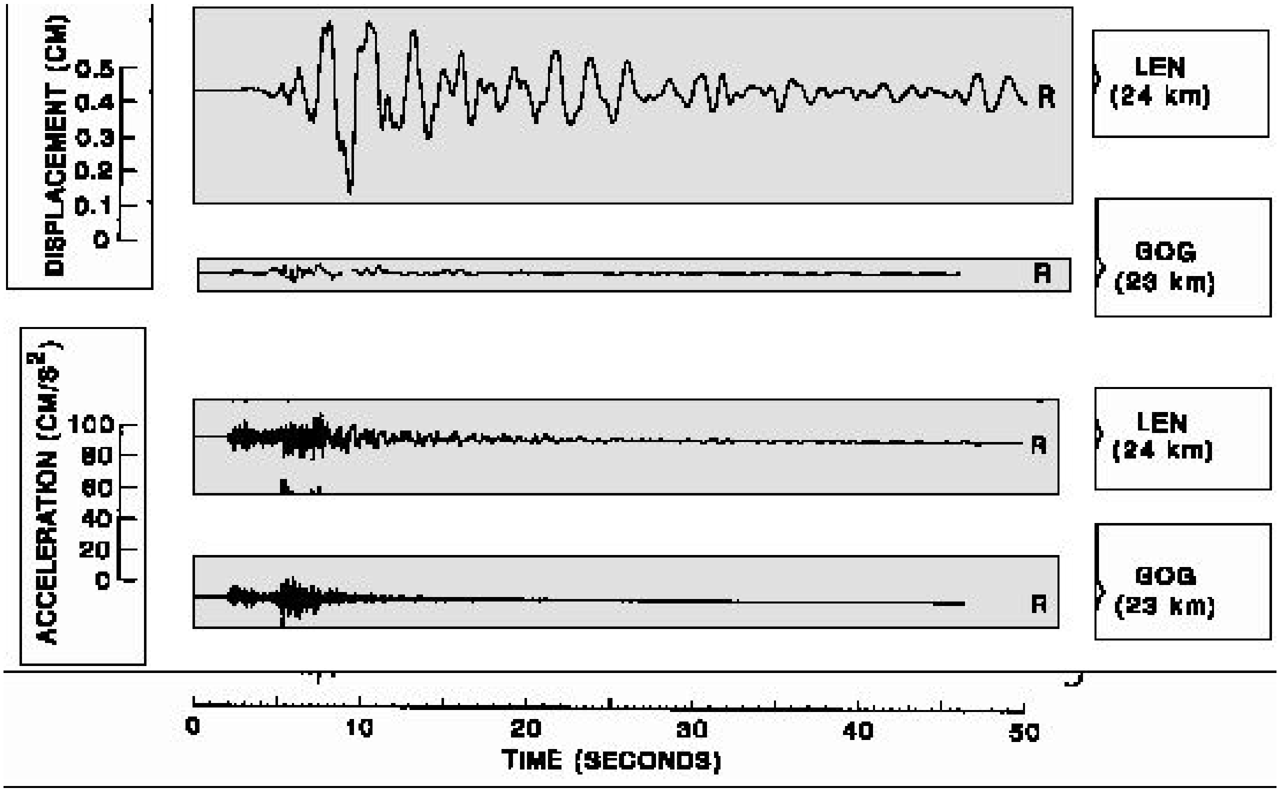

Fig.3 Seismograms and accelerograms, recording on stations *Len* and *Gog* at aftershock with magnitude 4,7 [6]

Hence, incorporation of site class factors, applied to correct seismic impacts on structures, results only in adjustment of design acceleration values and does not consider the true character of seismic impacts on constructions, located on the soft soils.

In conclusion, the unique impact of seismic events on sites with soft soils (category *D, E*), leads to greater displacement of bases and foundation.

Upon their subjecting to seismic waves, relative displacements of the bases of foundations along the length of a building can increase considerably (fig. 4) causing damage or destructions of buildings.

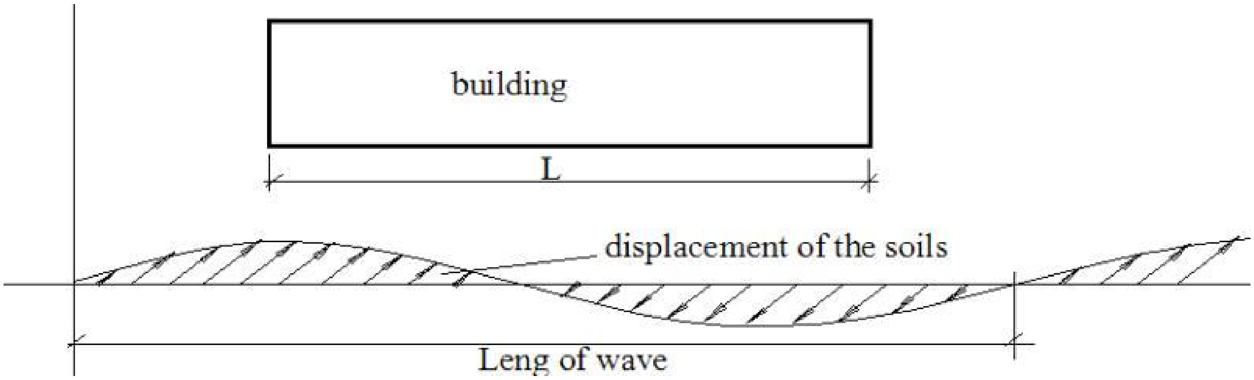

Fig.4 Displacement of the soils at passing of seismic waves

SUMMARY

Measured results for various types of buildings and soil types testify to the need to account for amplified displacements on soft soils, which is more pronounced for longer objects, bridges, etc. in which greater relative displacements of adjacent parts can be cause for significant damages/destruction at strong motion earthquake events.

Here, there is a doubt concerning concept of "Seismic joints or buildings separation". As in schemes of design, the basis of structures is initially accepted as motionless, naturally, that in building codes, a seismic joint typically creates a separation between the adjacent buildings or parts of buildings that includes separation of walls, floors, roof etc., but does not include separation of foundations. It is commonly practiced, that seismic joints or separation of buildings is used with the purpose of creation of conditions to isolate, and allow the free movement of adjacent buildings or parts of buildings during seismic events.

However, at unseparated, foundations of adjacent buildings, overall condition given above may become the cause of development of secondary stresses in the foundation and in the associated superstructures.

In our opinion, the assumption accepted in building codes, regarding not mandating separations of foundations is incorrect, and therefore, seismic separation that is commonly required should be extended to additionally include the below ground portion of a building, as well as the foundation .

This factor is critically important for soft soils, where the passage of seismic waves amplify relative displacements of the ground and the foundation, without a corresponding substantial growth of the acceleration.

Seismic separation of the building foundations does not require the implementation of seismic joints and does not increase the cost of construction.

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