Soil Structure Interaction for structures to be erected in complex geological conditions

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SUMMARY:
Problems of earthquake stability of structures to be erected in complex geological conditions are considered. Among structures under consideration there are large bridges and tall buildings, to be erected on soils with thyrotrophic, water-saturated, slumping layers. All structures have deep foundations. The most part of structures have special protection devices of seismic isolation and damping. They are to provide the elastic behavior of the main structure, foundation and bearing soil. To analyze the structure, foundation and soil behavior under seismic loads all calculations were carried out in two stages. At the first stage the soil area with a foundation but without a structure was studied. The process included analyzing the system under consideration using well-known methods for the finite element analysis for infinite medium. Some questions of setting the size of the design area, seizes of finite elements, Lysmer damper parameters and soil elastic parameters are discussed in the paper. As the result of the first stage, the transfer function or the response function of the soil base is obtained. For the second stage a simple soil base model is built. This model has the same transfer function or the response function as the first soil base model. The use of the simple base model makes it possible to analyze the soil structure interaction for rather complex structures. The response of the structure can be used to analyze the behavior of soil and foundation. For this purpose the first model is to be loaded with this response. The analysis of some structures behavior is considered in the paper. These structures include large bridges across the Amur River, the Amu-Daria River, the Golden Bay in Vladivostok and tall buildings with artificial bases in Ashgabat.

Key words: soil structure interaction, finite element analysis, rugged soil conditions

1. INTRODUCTION

At present more and more often engineers are facing problems of erecting structures on weak, water-saturated, thyrotrophic soils in seismic prone areas. The Russian Guidelines do not recommend such construction, but if it its necessary they demand corresponding scientific and technical support. In the former USSR a successful civil-engineering design of a region of Ashkhabad located on weak sagging soils was carried out from 1975 to 1990 using the condensed sandy- gravel pad of about 3 m deep under the buildings (Uzdin A.M., Sandovich T.A., Samich Naser, 1993).

Much more often it is necessary to face build bridges on weak soils for bridges. While it is possible to find a more favorable site for constructing a building it is impossible to remove a bridge from the river and therefore a part of the bridge piers turns out to be in difficult geological conditions. In this case two situations are possible:

- bedrock is located on the accessible depth allowing a pier to rest on the rock;
- bedrock is located too deeply and it is practically impossible for a pier to rest on the rock.

In both cases the estimation of seismic stability of the base and of the structure as a whole is rather the specific and presents certain difficulties for designers.

To estimate the of structure seismic stability, it is necessary to solve the following problems:

- to set the seismic input;
- to build a design diagram of the system « soil - structure» ;
- to write down the equations of the system under the seismic load;
- to offer a way of solving the equations;
- to choose the criteria of seismic stability of the considered system taking into account possible limiting conditions of the soil base.

There is much literature available on these problems. The most detailed description of the problem is given in two monographers of professor Wolf (1994). The analysis of the mentioned problems in Russia is to be found in publications of A.G.Nazarov (1939), V.A.Ilichev (1981), O.A.Savinov (1974), J.G.Tjapin (1994) and some other experts. Nevertheless, some of the problems have had no satisfactory decisions so fare. The difficulties arising at practical realisation of the listed problems are considered below and the engineering approach to solving them is proposed for calculating bridges.

2. EARTHQUAKE INPUT SETTING

The Russian Guidelines prescribe to set seismic input by seismic intensity on the MSK scale or by peak accelerations on a free day surface in the absence of a structure. Thus, the design input is set for average soil conditions. For weak soils in accordance with the Guidelines the intensity increases by one degree on the MSK scale, i.e. the design accelerations are doubled, and for rock soils the intensity decreases by one degree on the MSK scale.

Such approach causes serious objections even for usual structures. Up to now, despite numerous debates in Russia the seismic input level is to be set in agreement with the category of the soil prevailing in the top 10-metre thickness of the soil massive.

So, for a building site with a layer of dust water-saturated sands the thickness of 5.01 m on the rocky bed, seismicity should be increased in relative the average soil condituons and at the thickness of a layer equal to 4.99 m seismicity should be reduced in relative the average soil conditions. According to the Guidelines the change of the thickness of a weak ground by 2 cm results in the change of the design loads by 4 times. Such paradoxical requirement of the Guidelines causes not only bewilderment among designing engineers, but imposes incorrect engineering solutions on them. The loads increase inevitably leads to the structure strengthening. Meanwhile, such strengthening, in most cases, is not required. The increase of seismicity for building sites embedded with weak soils is connected with the increase of the building damageability. However in this case the connection between seismicity and peak accelerations is broken, because in practice seismologists do not observe the doubling of accelerations prescribed by the Guidelines. For weak soils the growth of damageability is caused by the ground structural failure, leading to relative foundation settlements or to the base soil liquefaction. In this situation the increase of rigidity of a building can be not only useless, but harmful. In this case investments should be made in preparing and improving the base.

For bridges the situation appears to be much more difficult. The foundations of bridges cut into the soil thickness from 10 m to 50 m deep. This soil thickness consist of weak water-saturation soils, and rests on the rocky base. Accordance to the soil properties under the foundation we can decrease the design seismicity, and according to the soil properties of the day surface it is necessary to increase seismicity. (Fig. 1) To improve the situation, it was proposed to set bridge seismicity, taking into account the top 30-metre soil thickness. However, it does not save the situation at all, but leads to new absurd results. For example, at the washout of the top soil thickness it can appear that in the top layer strong soils will start to prevail and the input level of the seismic load can be lowered twice.

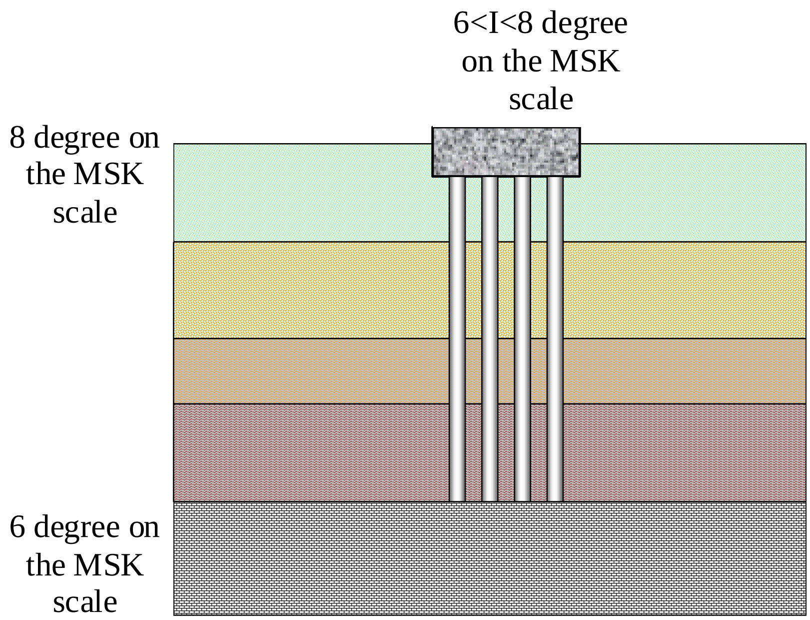

Figure 1. Explanation of earthquake intensity setting

While working out Specifications on designing some bridges, the authors used the following wording for structure calculation process: «to set the level of design input, taking into account soil conditions on the areal of application of the load in the design diagram». Such wording partly answers the questions asked, but it is necessary to remember that the ground above this area should be taken into consideration in the design diagram. It creates some additional difficulties for designers.

To summarize, we can say that it is rather difficult for designers to set design seismicity both for the bridge as a whole, and for each of the piers. The problem becomes even more complicated for the big bridges because the basic Guidelines hypothesis about synchronous excitation of all piers is absolutely unjustified.

3. THE DESIGN DIAGRAM OF THE « SOIL - STRUCTURE» SYSTEM

The proposed design procedure of the soil-structure interaction (SSI) analysis for bridges is based on the methods which take into account the general SSI approaches and methods of calculating multi-supported structures. For this aim we divide the solution of the problem into several stages.

At the first stage the system is divided into the rocky base and a massif of alluvial adjournment together with the bridge (Fig. 2). At the joint of the top and bottom parts, i.e. in the connection nods of the finite element net, the input is given to them from the basement rock. In this case the input level is set for the structure as a whole, taking into account geological properties of the basement rock. The input is set taking into account the finite speed of wave propagation in the basement rock.

At the second stage a part of the base of each pier is singled out and analysed separately. Thus, the soil "box" with a part of the pier base is separated from the soil massif. (Fig. 3) The detailed finite-element analysis of the system is used for estimating the “box” dynamic properties. The Lysmer damping boundary is shown by dotted lines along the side boundary of the design area.

The finite-element analysis of the system is characterized by the following peculiarities

- The main design characteristic of the soil in accordance with the Russian standards is the module of soil general deformation E_0. The module of elasticity one can be set using the value of E_0 Both the value of E_0 and that of E change along the depth of the soil massif.

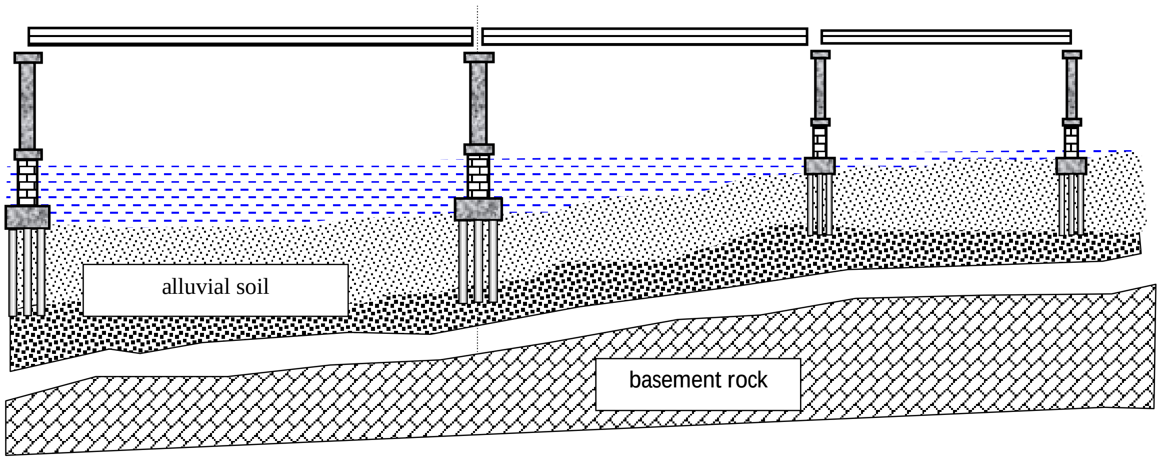

Figure 2. The division of the system into two subsystems - the basement rock and alluvial adjournment together with the bridge

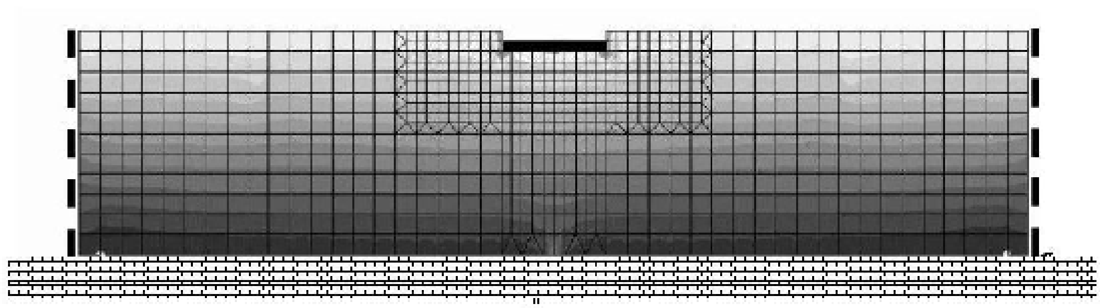

Figure 3. Finite element design diagram

- Down to depth of 15 m it is considered to be linearly increasing

$$E_0 = 2.3\rho g z \cdot \frac{1-\varepsilon}{C}, \tag{1}$$

where ε is the porosity indicator, C is the factor of compressive pressure, ρ is the ground density, g is the gravity acceleration.

If the “box” is more than 15 m deep the elasticity module is set using the following law

$$E(z) = E_\infty \cdot \left(1 - e^{-\alpha z}\right) \tag{2}$$

Parameters E_∞ and α are set on the basis of experimental data or using approximating dependences. In our calculations dependences E(z) obtained by Professor L.R.Stavnitser (2010) are used.

- The Lysmer damping boundary is placed on a lateral surface of the cut out area i.e. on the “box” boundary (Fig. 4). In practice, in each knot of the boundary are placed vertical and horizontal dampers, providing the absorption of energy equal to its radiation on infinity by elastic waves

For the above-mentioned finite-element base model transfer functions $\Phi_{xx}(w), \quad \Phi_{jj}(w), \quad \Phi_{xj}(w).$ are built. Using these functions a model of the base including springs, lumped mass and dampers is built. This model is shown in fig. 5. It must provide the proximity of the obtained transfer functions of the finite-element base model to those of the simplified model.

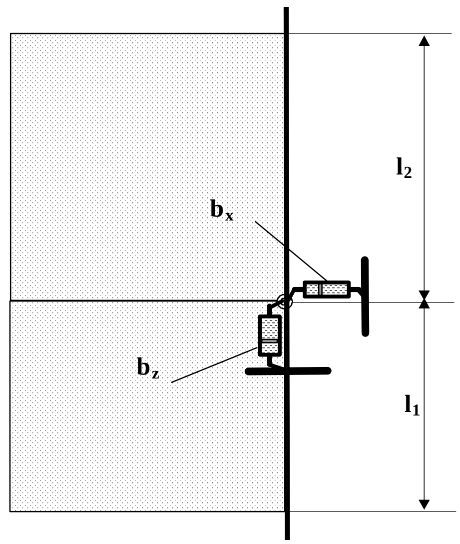

Figure 4. The diagram of dampers placing in the knots of boundary

The model parameters including weights, rigidity, damping and the distances A1 and A2 between the dampers are defined by the least square method, minimising the error between the transfer functions of the complete and simplified models.

The simplified base model is used to analyse the bridge behavior as a whole.
At the third stage calculating the bridge with using simplified base model (a Fig. 6) is carried out. In this calculation the seismicity is taken into account according to the soil properties of the base rock supporting the structure in the design diagram.

Finally, at the fourth stage the seismic reaction obtained for the top foundation plate at the third stage is regarded as loading to the respective nods of the finite-element scheme constructed at the first stage. In this loading stresses in elements of the base and foundation are defined.

1. SOME PECULIARITIES OF THE SSI ANALYSIS

The analysis of the SSI of a bridge is characterized by two important peculiarities.

The first peculiarity is important both for calculating transfer functions and the structure analysis using the simplified base model. This peculiarity caused by inhomogeneous damping of the system. The process of transfer functions definition is to use the damping boundary parameters. The letter can be much bigger than those of the soil massif and foundation and the value of damping is proportional to acoustic stiffness $\sqrt{E\rho}$, where E is the soil elastic module and ρ is the soil density. The same situation takes place in calculating the structure with the simplified base model. Bridges include at least three parts: spans, piers and foundations. Besides, it is necessary to take into account permanent way, bearings, seismic protection devices etc. Steel spans are characterised by hysteresis damping with the damping ratio $\zeta \approx 2.5$ % of the critical value, reinforced concrete piers are characterised by the damping ratio $\zeta \approx 3.5$

- 5 % and the soil thickness has hysteresis damping with the damping ratio ζ≈5 - 10 % of the critical value. The base model is characterised by viscous damping, which leads to energy losses exceeding considerably the hysteresis ones.

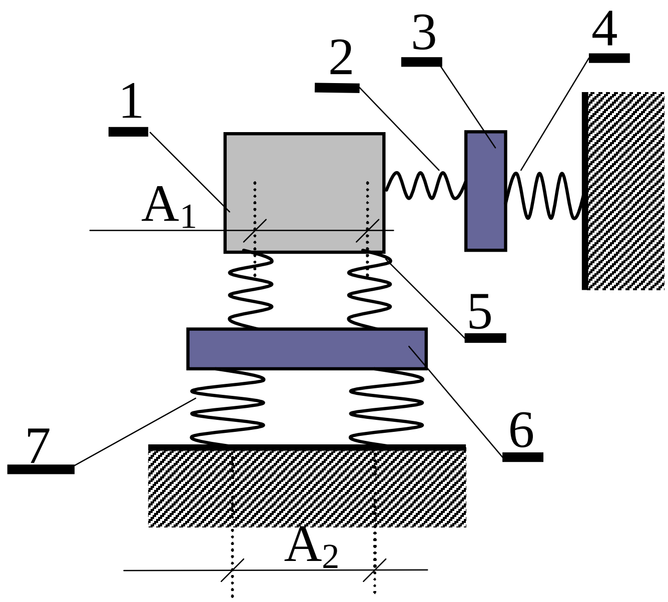

Figure 5. The simplified base model

1 – the foundation mass with the attached ground mass*; 2* – the first reduced base stiffness in the horizontal direction, modeled by a spring with stiffness K_{X1} and damping characteristic z_{1X}; *3* – the reduced soil mass m_x; *4* - the second reduced base stiffness in the horizontal direction, modeled by a spring with stiffness K_{X2} and damping characteristic z_{2X}; *5* - – the first reduced base stiffness in the vertical direction, modeled by a spring with stiffness K_{Z1} damping characteristic z_{1jZ}; *6* – the reduced soil mass m_z; *7* - – the second reduced base stiffness in the vertical direction, modeled by a spring with stiffness K_{Z2} and damping characteristic z_{2jZ}

To account this fact, seismic loads estimation demands building the damping matrices of the systems under consideration. On its basis the damping spectrum, including damping ratios for each mode, is to be obtained. Amendments to seismic forces separately for each mode are entered using these damping ratios. The technique of the mentioned procedure is described in details in publications (Petrov V. A, Uzdin A.M., 2004; Pejchev M.M, Uzdin A.M.,2001)) and the textbook (Eliseyev O. N, Uzdin A.M.,1997).

Versions of the programs ANSYS, ABACUS and MIDAS being used in Russia, include two variants of integration, namely: using the modal decomposition of oscillation equations and using the procedure of their direct integration. Using the first way we do not take into account the influence of damping on structure modes which can lead to essential errors. Using direct integration which takes into account inhomogeneous system damping can give unpredictable incorrect results. It demanded that the authors should work out the auxiliary programs and solve the problems of testing.

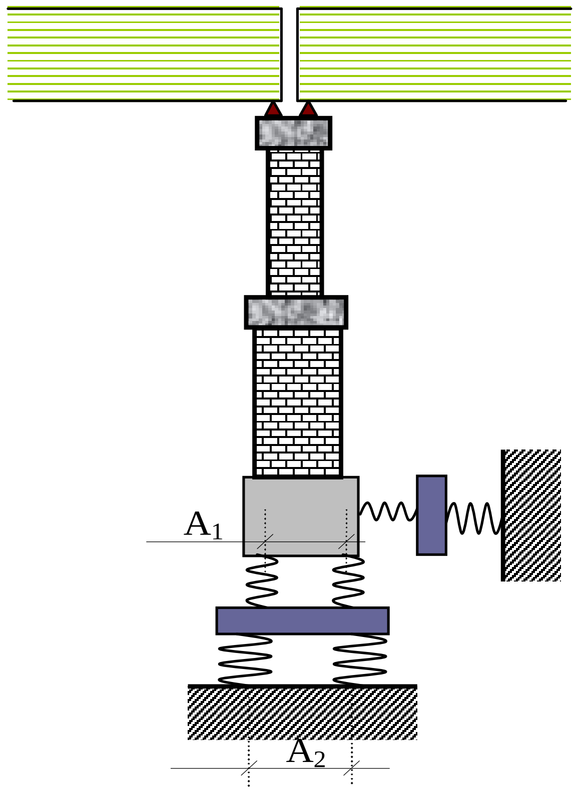

Figure.6. Fragment of the design diagram “soil-structure”

The second peculiarity, the heterogeneity of acceleration field along the bridge is important in analyzing the bridge with the simplified base model. The problem is due to the finite velocity of wave propagation along the bridge and heterogeneity of soil conditions along the structure. In calculating statically determinate bridges under design earthquake loads the account of nonsynchronous pier excitations results in decreasing the design loads and in the first approximation can be ignored. In other cases this account is necessary. For statically indeterminate systems there can arise stresses due to mutual displacement of structure members. In all cases the nonsynchronous excitation predetermines results of the structure kinematic calculation under the impact of maximum design earthquake.

To take into account the considered factor, the authors developed a design procedure in which structure seismic forces are estimated separately from excitation of each pier [6,7]. In this case, there are as many matrices of seismic forces as there are piers in the bridge. The system stresses, caused by mutual displacement of piers are calculated separately. The summation of stresses and displacements for each mode caused by from excitations of different piers is carried out taking into account their correlation.

2. AN EXAMPLE

As an example in fig.7 are shown the dependencies of the accelerations on the depth of the soil near the foundation and at some the distance from it for the large pier of the bridge across the Golden Horn bay in Vladivostok. It can be seen that accelerations increase 4 fold from the rocky base to the surface of the soil massif. It is caused by the fact that the top 10 m of the base consist of weak water saturated soils. However this effect is not observed near the pier. The pier rests on the rocky base and prevents the ground from swinging with significant loadings being transferred to the pier foundation as a result of seismic pressure of weak soil.

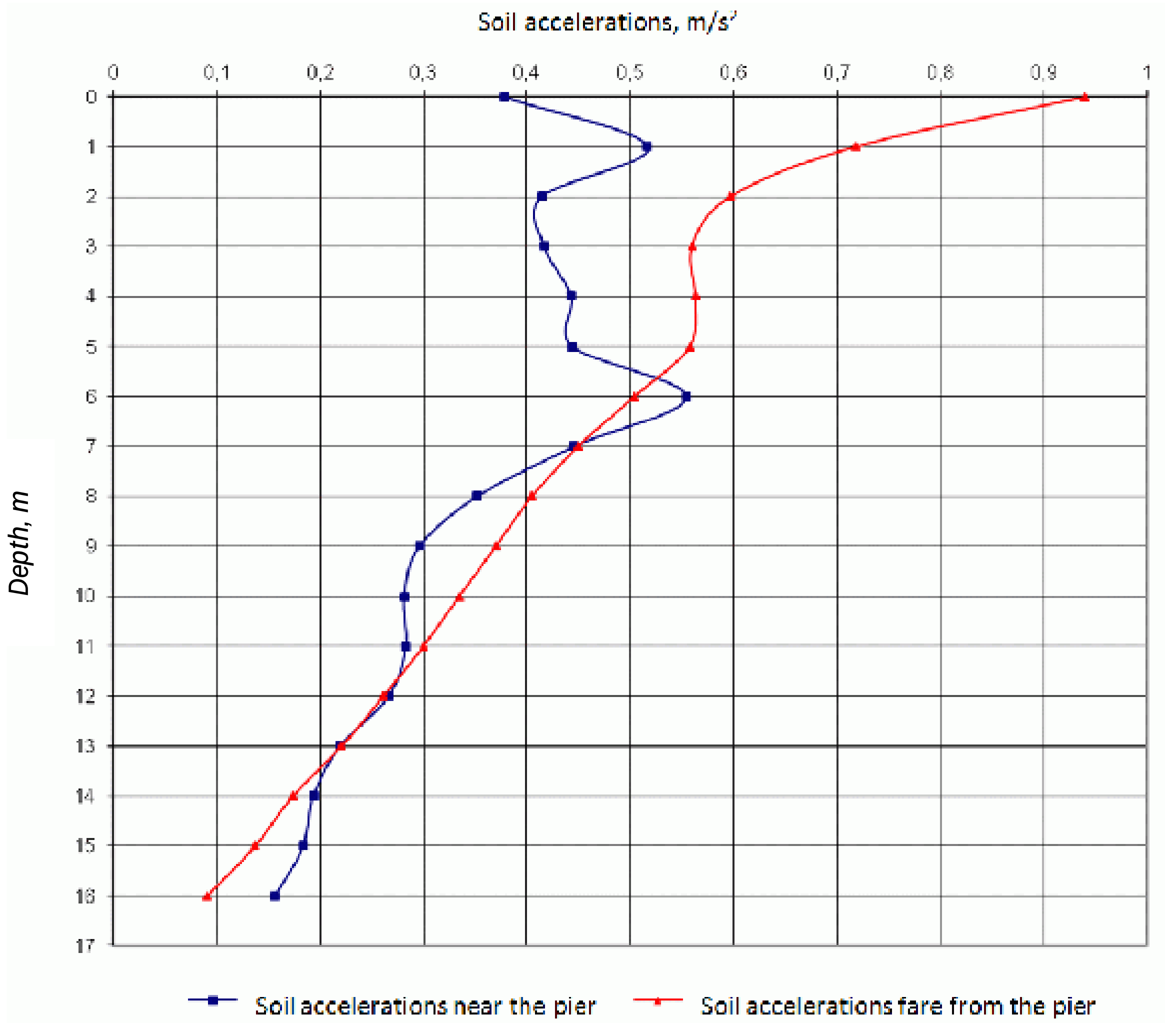

Figure 7. The dependencies of the accelerations on the depth of the soil near the foundation and at some the distance from it for the large pier of the bridge across the Golden Horn bay in Vladivostok

AKNOLEGMENTS.

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