Copyright © 1996 Elsevier Science Ltd
Paper No. 36. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

THE INFLUENCE OF THE EMBEDMENT DEPTH ON THE SEISMIC RESPONSE OF HEAVY RIGID STRUCTURES

A.G.TYAPIN

Department of Seismic Safety,
"Atomenergoproject" Institute, Moscow
Slaviansky boul., 1-119. Moscow 121352 Russia

ABSTRACT

Seismic response of heavy rigid structures like NPP reactor buildings is greatly influenced by the embedment of the foundation. SSI effects caused by the embedment of the rigid foundation are studied, basing on general decomposition approach. Some additions to the conventional engineering methods are proposed, enabling to estimate the response of the embedded structures on rigid basements.

KEYWORDS

Soil-structure interaction; linear soil; embedment with full contact; rigid basement; decomposition; seismic excitation forces; dynamic stiffnesses in the frequency domain; optimal embedment depth.

GENERAL APPROACH

Embedment of foundation in a soil stratum may greatly influence seismic response of structure. Two main ways for such an influence are frequency/damping characteristics of the soil-structure system and characteristics of the effective excitation due to the seismic wave. The first aspect has been studied intensively (summary is given, for example, by Gazetas, 1991). This report presents some results on the second aspect of the problem.

Rigid foundation separates two flexible parts of the soil-structure system (the upper structures and soil), thus enabling to apply decomposition. For the linear soil and structural models seismic loads are described by 6 general forces $B_j(t)$, $j=1,2,...,6$ (Fig.1), acting on the basement. These are the forces, arising from the seismic wave when the basement is immovable (they do not include additional forces, acting from the soil due to the vibration of the basement). Such application of superposition (allowed due to the linearity of the soil medium and full contact between soil and basement) is alternative to the well-known one (Kausel *et al.*, 1975) based on kinematic and inertial interaction.

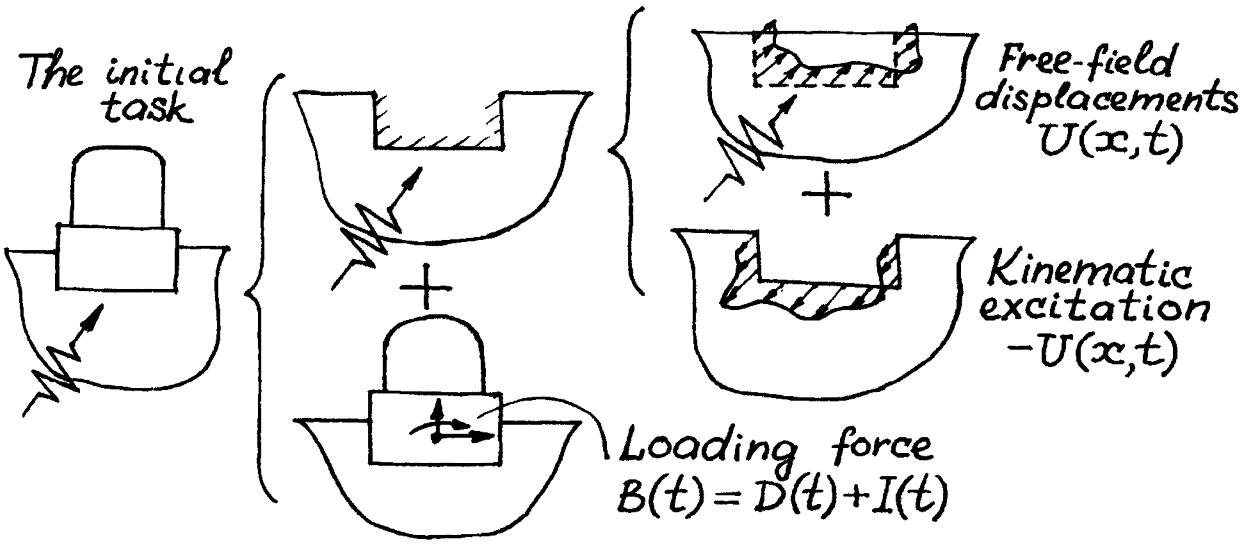

Fig.1. Superposition of tasks for linear soil model

The same superposition principle allows to divide forces $B_j(t)$ into two parts: the first one $D_j(t)$ arising from the falling free-field wave U(x,t) and the second $I_j(t)$ arising from the wave, reflected from the immovable basement. In fact the second wave field may be described as the reaction of the soil to the kinematic excitation -U(x,t) applied at the contact surface (see Fig.1). Let operator P[V(x,t)] describe wave field of such type, caused by kinematic excitation V(x,t) at the contact surface. Then the wave field around the immovable basement is W(x,t)=U(x,t)-P[U(x,t)]. Let S{W(x,t)} be the field of surface distributed forces, acting on the basement from the soil with wave field W(x,t). To obtain j-th component of general force from the field S, it must be multiplied by some other field $e_j(x)$ and integrated over the contact surface A.

$$B_j(t) = \iint_A S\{U(x,t)-P[U(x,t)]\}\, e_j(x)\, dA \qquad (1)$$

For j=1,2,3 the field $e_j(x)$=const(x) (e_j are just orts, applied throughout the contact surface). For j=4,5,6 the field e_j depends on x. Generally speaking, $e_j(x)$ is vector of displacement in the point x in case of rigid unit displacement of the basement along the coordinate j. According to the definition given above

$$D_j(t) = \iint_A S\{U(x,t)\}\, e_j(x)\, dA \qquad (2)$$

$$I_j(t) = -\iint_A S\{P[U(x,t)]\}\, e_j(x)\, dA \qquad (3)$$

The force $D_j(t)$ may be obtained from the free-field accelerations a(x,t) and soil density r(x) inside the excavated soil volume V:

$$D_j(t) = \iiint_V r(x)\, a(x,t)\, e_j(x)\, dV \qquad (4)$$

If the basement is not embedded, V=0 and D_j=0. If the prismatic basement is embedded to the depth h and the excavated soil is homogeneous, then for the vertically spreading seismic wave approximately

$$D_j(t) = M_s\, a_j(h_1,t)\,,\ j=1,2,3 \qquad (5)$$

Here M_s is the mass of the excavated soil, and the acceleration a_j is taken from the depth $h_1 = h/1.732$. To take into account rocking and torsion, forces (5) are to be applied in the gravity center of the excavated soil. Analysis in the frequency domain shows satisfactory accuracy of these approximate results.

It may be shown rigorously (some general reciprocy theorem), that in (3) two displacement fields U(x,t) and $e_j(x)$ can change their places (unfortunately, only in the frequency domain)

$$I_j(w) = -\iint_A S\{P[U(x,\omega)]\}\, e_j(x)\, dA = -\iint_A S\{P[e_j(x)]\}\, U(x,\omega)\, dA \qquad (6)$$

Distributed forces $S\{P[e_j(x)]\}$ are that very forces, arising in the "standard contact tasks" (when rigid basement moves along coordinate j with unit amplitude and given frequency ω), that are used to obtain dynamic stiffnesses of the basement

$$C_{jk}(\omega) = -\iint_A S\{P[e_j(x)]\}\, e_k(x)\, dA \quad , j,k=1,2,...,6 \qquad (7)$$

Hereafter, "dynamic stiffness" $C_{jk}(\omega)$ means complex frequency-dependent amplitude of the force, acting along coordinate j from soil on the basement in response to the harmonic displacement of the basement along coordinate k with unit amplitude and frequency ω.

Equations (6) and (7) mean that "standard contact tasks" bring all the information, necessary for SSI analysis with arbitrary free-field motion U(x,t) and embedment, thus eliminating special tasks for"kinematic interaction" or "effective excitation". This information, however, is given not in the form of dynamic stiffnesses $C_{jk}(\omega)$ but in the form of the distributed complex frequency-dependent contact forces $S\{P[e_j(x)]\}$ forming both dynamic stiffnesses $C_{jk}(\omega)$ (through (7)) and one part of the effective seismic load $I(\omega)$(through (6)). Another part $D(\omega)$ is formed by the free-field seismic wave and inertia of the excavated soil (through (4)).

As a result of (6) and (7), if the wave field $U(x,\omega)$ is "rigid in V", i.e. throughout A

$$U(x,\omega) = \sum_{j=1}^{6} U_j(\omega)\, e_j(x) \quad , \qquad (8)$$

then

$$I_j(\omega) = \sum_{k=1}^{6} C_{jk}(\omega)\, U_k(\omega) \qquad (9)$$

The example of the "rigid in V" wave field is vertical wave for surface basement, when $D_j=0$ and (9) allows to use a "platform" model. Platform model means the structure model, connected to the rigid platform by "soil springs". Platform is shaked by some kinematic excitation (for the surface basement and vertical wave this excitation is simply free-field motion U(t)). "Soil springs" mean some system, having stiffness matrix $C(\omega)$ - complex and frequency-dependent with 6*6 elements $C_{jk}(\omega)$, equal to the dynamic stiffnesses (7). This system must provide given forces acting on the basement not only for the moving basement and the immovable platform, but also forces (9) for the immovable basement and the moving platform. If only springs and dashpots are used to model "soil springs", then these two conditions are met simultaneously, but if there are additional "soil" masses (often used to model frequency-dependent decay of stiffnesses), then the additional exciting forces must act on these masses together with shaking of the platform. It may be shown rigorously that for "soil mass" m such a force must be ma(t), where a(t) is the acceleration of the platform. If the task is solved in the coordinate system, moving together with platform, inertial forces -ma(t) are added to all the masses in the soil-structure model. For soil masses the resulting forces will be zero, thus matching the well- known platform model with exciting seismic forces.

For the embedded basement the wave field $U(x,\omega)$ is not "rigid in V", but (9) is still valid, if $U_k(\omega)$ mean free-field displacements, averaged over the contact surface according to (6) with weights, proportional to the contact forces $S\{P[e_j(x)]\}$. The greater is coefficient A_b/A_w (A_b - area of the bottom, A_w - area of the embedded walls), the closer is the averaged excitation U to the free-field motion at the bottom. Note, that for vertical seismic waves near the surface the deeper is the point, the less are seismic displacements and accelerations. That is why the depth h_l may be set as a point for taking $U(\omega)$ with some conservatism. Then the platform model may be used for seismic analysis of the embedded structures with three additions:

- the additional force $D(t)=M_s a_l(t)$ is applied in the gravity center of the excavated soil, M_s being the mass of it (if the task is solved in the moving coordinates, this force remains untouched because no inertial force appears for the absent mass M_s);
- the platform is shaked by seismic accelerations $a_l(t)$, taken not from the free field surface, but from the non-outcropped free-field depth h_l (for prismatic basements $h_l=h/1.732$);
- embedment must be taken into account while obtaining dynamic stiffnesses (including the increasing role of the lateral-rocking coupling).

INFLUENCE OF THE EMBEDMENT ON RESPONSE

All three listed factors change seismic response of the structure with embedded basement compared to the same structure with surface basement subjected to the same seismic wave. If the task is solved in the moving coordinates, the force D(t) is directed opposite to the inertial forces acting on the structure, thus mitigating the difference between the response motion and the free-field one. For example, if rigid structure is fully embedded in soil and it's gravity center and mass are the same as of the excavated soil then the response is approximately equal to the free-field $a_l(t)$. The influence of the additional force for prismatic basement is approximately proportional to the embedment depth h. Approximately the response accelerations may be corrected by the coefficient

$$k_l=1-(M_s/M_b)(1-1/k) \quad (10)$$

with M_b being the mass of the structure and k being the former amplification factor (ratio of floor response spectra to the excitation one for the surface basement case). Numerical example: for the NPP reactor building embedded in soil for 10 m the ratio M_s/M_b is about 0.3. For k=3 the reduction is 20%.

The influence of the second factor depends on the frequency content of the excitation. For vertical harmonic wave, spreading with velocity v and frequency ω the reduction coefficient is approximately

$$k_2=1-(\omega h/v)^2/6 \quad (11)$$

For heavy rigid structures ω can be estimated as the first natural frequency of the soil-structure system in a given direction. For NPP having the first frequency about 2 Hz with h=10 m and V_s=400 m/s the reduction is about 1.5% which is negligible. However, using SHAKE, more significant reduction can be obtained, because maximum accelerations are often caused by high-frequency components. This question - modification of design response spectra considering the depth of embedment - must be studied further.

Speaking of the third factor two types of soil foundations must be distinguished one from the other. The first type sites are formed by soil stratum, underlain by bedrock. It is well-known (e.g.,Wolf,1985) that such a site has natural eigenfrequencies, the first of them ω_0 being the "the cut-off frequency", limiting propagation of surface waves. It may be shown rigorously, that surface basement provide the first sway-rocking eigenfrequency of the soil-structure system always less, than that of the free soil. Thus, the first resonance is damped only by the material soil damping, resulting in high peaks of the transfer functions in the frequency domain from the free field to the floor response.

Due to the embedment the stiffness of the basement in the soil may be increased so, as to set the first eigenfrequency ω_1 (which is the eigenfrequency of the structure on the soil) above the natural soil one ω_0. In this case the first structural resonance is damped both by material and by wave soil damping (in fact, it is often overdamped). The example was given by the author (Tyapin, 1991) for NPP reactor building, though some explanations have turned to be incomplete. The increase in horizontal dynamic stiffness in the frequency domain due to the increase in the embedment depth is shown in Fig.2 (curves 1...5).

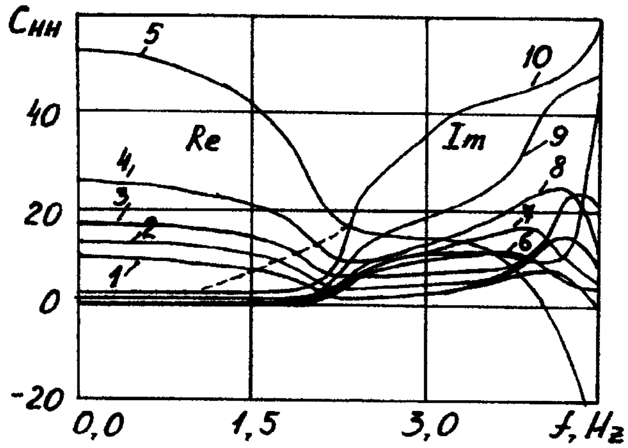

Fig.2. Horizontal dynamic stiffness C of rigid basement embedded in three-layerd soil stratum. Curves 1...5 - Re C for embedment depth 0;4.5;9;13.5;18 m. Curves 6...10 - Im C for the same depth.

Dashed curve shows parabola $M_b\omega^2$. Crossing points of this curve and curves 1...5 approximately mark the first eigenfrequencies of the soil-structure system. Absolute values of the transfer functions from the horizontal movement of the bedrock to the horizontal movement of the top of the basement are shown in the Fig.3.

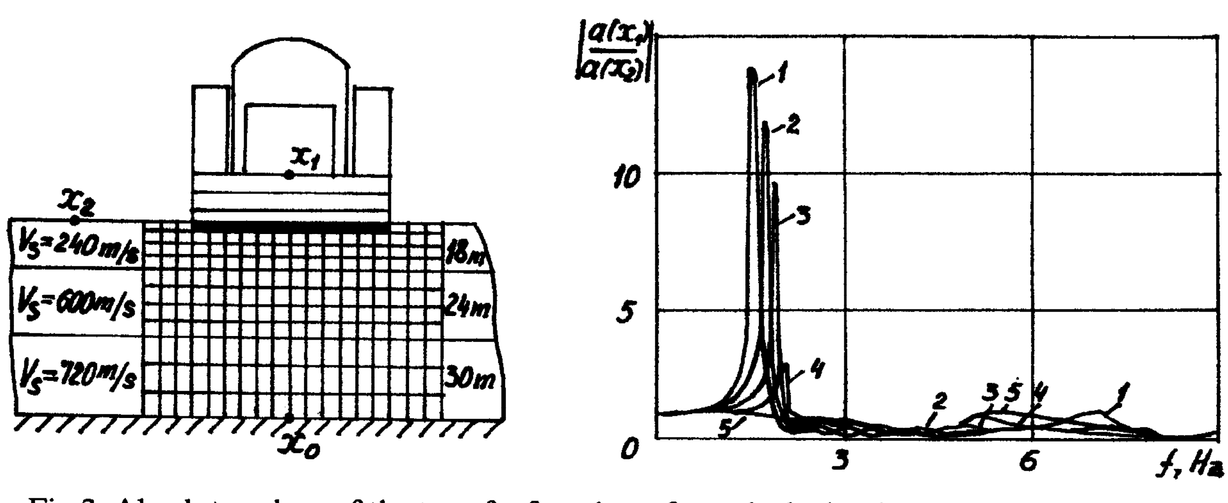

Fig.3. Absolute values of the transfer functions from the bedrock to the top of the basement

The decrease in peaks from curve 1 to curve 3 is explained not by the increase in damping (see Fig.2), but by the factor of the "excavated soil" k_1 (10). The further reduction (curve 4) is due to both factors, because the relative damping near the "soil" frequency ω_0 starts to rise. Curve 5 in Fig.3 shows no peaks: $\omega_1 > \omega_0$ (see Fig.2) and the first resonance is overdamped.

This example shows, that (10) can decribe the embedment effect for low frequencies, when almost no structural flexibility occurs. For higher frequencies which are closer to the partial eigenfrequencies of the building itself, the influence of embedment on the response is far more complex. The stiffer is the basement in a soil, the more important is the role of structural deformation, damped only by the material damping in the structure. If the structure is embedded up to the bedrock, no soil damping occurs and the response of the upper floors is high. So, there appears the "overembedment" effect for the upper floors of the structure. As a result, there must exist some "optimal" depth, providing minimum seismic response for the given floor. Numerical examples show the 50% mitigation of seismic response,
compared to the surface foundation for the sites of the first type.

The second type sites have no bedrock (at the visible depth) and no natural eigenfrequency. But the "excavated soil" force still acts, mitigating the total load and the response. The increase in stiffness and damping due to the increase in the embedment depth is still present, though not so dramatical, as for the first type sites, so the effect of the "optimal" depth is valid here also, but the percentage of the response mitigation is less (about 20...30% in the examples considered).

CONCLUSIONS

1. For structures built on rigid basements all the information about SSI may be given in terms of the free-field wave at the basement-soil interface and of the distributed complex frequency-dependent contact forces acting on the basement from the soil in the set of "standard contact tasks" and forming both dynamic stiffnesses and one part of the effective seismic loading force. Another part of the seismic loading force is formed by the free-field seismic wave and the inertia of the excavated soil. This part mitigates total seismic load compared to the case of surface basement. Thus no special tasks about "kinematic interaction" or "effective excitation" are needed even for embedded structures and arbitrary free-field seismic waves.

2. Approximate platform model is proposed for the analysis of the embedded structures with kinematic excitation, taken from some non-outcropped depth in the free-field seismic wave and with additional seismic force, proportional to the same kinematic excitation. Approximate formulae are proposed to take this factor into consideration in engineering analysis.

3. The embedment leads to the increase in soil-basement stiffnesses and in the first structural-soil eigenfrequencies. They approach the first eigenfrequencies of the flexible upper structures, thus leading to the increase in seismic response on the upper floors. On the other hand, the increase of the first soil-structural eigenfrequencies for the sites underlain by bedrock and for certain embedment depth enables wave damping to mitigate total seismic response. For the upper floors due to the above mentioned effects there may appear the effect of the "optimal depth". For the first type sites (with shallow bedrock) the response may be two times mitigated compared to the surface basement; for the second type sites (without bedrock) mitigation is less but still exists.

REFERENCES

Gazetas, G. (1991) Foundation vibrations. In: *Foundation engineering handbook* (H.Y.Fang, ed), pp.553-593. Van Nostrand Reinhold.
Kausel, E., R.V.Whitman, F.Elsabee and J.P.Morray (1977) Dynamic analysis of embedded structures. *SMiRT-4*, K 2/6.

Wolf, J.P. (1985) *Dynamic Soil-Structure Interaction*, Prentice-Hall, Englewood Cliffs, N.J.
Tyapin, A.G. (1991) Influence of embedment on the first resonance of soil-structure system. In: *Earthquake Engineering: Proceedings of the 16th Regional European Seminar*, pp.220-226. Rotterdam, Balkema.