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INFLUENCE OF EARTHQUAKE HYPOCENTER LOCATION ON SOIL-STRUCTURE DYNAMIC BEHAVIOR

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Abstract. A new numerical method for large-sized buildings seismic resistance modeling is proposed. It assumes various factors: contact interaction with soil, gravity field, ground non-homogeneity and earthquake hypocenter location. Deep and shallow earthquakes modeling methods are proposed additionally. It is shown that the location of the seismic source has different effects on the behavior of different types of structures during earthquakes.

1. Introduction

Building regulations stipulate seismic resistance calculation weakly deepened structures using a simplified model of soil. For deep foundation structures and adjacent underground pipelines seismic resistance investigation, a massive soil block adjacent to the structure should be taken into account. The soil block size should minimize the reflection from the boundary wavesin the near to the building area. The accurately describing of structures and high-frequency seismic oscillations leads to significant complexity increase of the numeric modeling of big-size seismic tasks based on differential methods.The soil and deep foundation structures long-term dynamic interaction modeling method, described in [1], assumes soil-structure interaction and might significantly decrease the computation costs.

2. Mathematical model

In the framework of solid medium mechanics hypothesis, it is utilized the variation principle for solid deformation description. In the static Cartesian coordinate system $Oxyz$ the medium displacement is characterized by Lagrange variables equations derived from D'Alembert-Lagrange variation principle

$$\iint_{\Omega} \left(\frac{1}{2} \sigma_{ij} (\delta \dot{u}_{i,j} + \delta \dot{u}_{j,i}) + \rho \ddot{u}_i \delta \dot{u}_i - \rho f_i \delta \dot{u}_i \right) d\Omega - \int_G p_i \delta \dot{u}_i dS - \int_G q_i \delta \dot{u}_i dS = 0 , \quad (1)$$

where σ_{ij}, e_{ij}, – are stress and deformation tensors components; $\dot{u}$ – displacement parts velocities; p_i, q_i – surface force and contact pressure components; f_i – volume force components, normalized to mass units (i=x,y,z).

Under given initial and boundary conditions the defining equation system (1) solution derivation is based on variation-difference spatial domain discretization method, complemented by time domain explicit integration scheme [2]. The solid medium deformation time domain process utilizes the time layer split approach: $t^0, t^1, \ldots, t^k, \ldots$ with time step of: $\Delta t^{k+1} = t^{k+1} - t^k$, derived from the Courant's stability condition. The scheme for integrating of the discrete analogue the equations of motion in time domain is represented as:

$$\left(\dot{u}_i\right)_j^{k+\frac{1}{2}} = \left(\dot{u}_i\right)_j^{k-\frac{1}{2}} + \frac{\left(F_i\right)_j^k \Delta t^{k+\frac{1}{2}}}{\left(M\right)_j^k},$$

$$\left(u_i\right)_j^{k+1} = \left(u_i\right)_j^k + \left(\dot{u}_i\right)_j^{k+\frac{1}{2}} \Delta t^{k+1}, \tag{2}$$

$$\Delta t^{k+\frac{1}{2}} = \frac{\Delta t^{k+1} + \Delta t^k}{2}, \left(i = x, y, z\right),$$

where F_i –generalized powers, affecting the node *j*, *M* – the mass, concentrated in the node *j*.

The soil massif is represented in a form of parallelepiped with a size of 20 times of planned typical building foundation size, thus avoiding the calculation results distortion by the boundary effects impact in the near to the building area [1]. The homogeneous or multi-layer perfectly elastic medium approach is sufficient for hard soil, while for soft soils the transversal-isotropic model taking into account its mechanical properties dependence of depth is utilized [3]. The gravity forces influence the computational domain. Depending on the location of hypocenter of earthquake the seismic impact is applied in a form of velocity vector components to the bottom or side boundary of the soil domain – v_x, v_y, v_z, while for the remaining domain sides the non-reflecting wave boundary conditions are modeled. The soil-structure interaction modeling assumes the presence of the dry friction: the perpendicular to the contact surface components q_i are derived from the non-penetration condition, tangent action components – from the Amontons-Coulomb’s law. The described methods, algorithms of contact interaction and the gravity forces assuming are realized in a certified software package – “Dynamica-3” [4].

3. Seismic impact modeling

During the mathematical formulation of construction seismic vibrations problem the issue related to seismic oscillations modeling methods arises. The seismic wave’s amplitude characteristics and direction of propagation uncertainties bring additional complexity to the problem resolution. The accelerograms, which are available from the experiments or synthesized by other equipment, will define the surface points kinematic characteristics. For seismic resistance numeric investigation the kinematic or force boundary conditions are required which aim to reproduce the known accelerograms in the near building area once defined on the edge of computational domain. The single surface point impulse load calculation problem based on given accelerogram looks incorrect due to earthquake source location uncertainty thereby causing the seismic wave’s velocity vector uncertainty. The appropriate setup of the seismic oscillations source location let the problem of derivation of domain boundary impulse load applied in accordance to known at half-space surface accelerogram to define properly.

There is a number of various seismic impact modeling approaches defined in the literature. The source of “falling weight” type, which generates the surface waves, is proposed in [5]. Kinematic boundary conditions at the lower boundary of the computational domain, realizing the flat seismic wave’s propagation in the direction, which is perpendicular to the ground surface, are considered in [6]. The shear model perturbation in the hypocenter corresponding geological fault and generates a cylindrical wave is described in [7].

The numerical method of kinematic boundary conditions derivation, proposed by authors in [9] relies on the assumption that the waves arriving to the building from the earthquake source are considered to be flat and propagate perpendicular to the ground surface, which corresponds to the directly under the building earthquake hypocenter location. The method assumes that seismogram at the surfacecanbe represented as a discrete decomposition: $C_1\left(t_h\right)=\sum_i a_i H(t_h-t_i)$, where a_i – amplitude seismogram at control point, $H(t\text{-}t_i)$ – Heaviside function, t_i – time offset seismogram point from the beginning of the reference seismogram on the surface. At the first stage, the one-dimensional problem of wave propagation, defined in the Heaviside form at the bottom boundary of the domain, should be resolved utilizing the grid-characteristic method. Once the calibration function changing after the soil propagation is derived, one can restore the desired seismogram at the bottom boundary of the computational domain for all the control points, utilizing the experimental discrete seismogram

$$\frac{H_1\left(t\right)}{H_0(t-t^*)}=\frac{C_1\left(t\right)}{C_0(t-t^*)},$$

where H_0 – calibration function; H_1 – one-dimensional problem solution on the surface; t^* – the propagation time of the wave from the lower boundary of the soil mass to its surface. The p-waves and s-waves seismograms at the boundary of the computational domain can be derived separately utilizing the linear interpolation between control points. The differential grid step is defined by the seismogram high-frequency oscillations definition accuracy.

The position determination of the seismic source in numerical modeling of the seismic action should be based on the statistics of earthquakes. Based on the last 15 years National Earthquake Informational Center (NEIC) of the US Geological Survey [8] data: 8 % of total number of earthquakes with >6 magnitude belong to deeper-focus (with more than 300 km focal depth), while 12 % – are intermediate and 80 % – are shallow earthquakes (less than 70 km focal depth). Taking into account decreasing of the magnitude of registered seismic vibrations due to partial decay in the soil, one can evaluate the applicability of the various seismic impact models. The model, described in [9] provides quite accurate description of deep-focus earthquakes and capable to provide robust seismic resistance estimates for selected construction site under maximum calculated earthquake loads, which corresponds to the epicenter located building case. The model [9] covers less than 1 % of expected earthquake square and does not consider Rayleigh surface waves impact to seismic action for shallow-focus earthquakes. Therefore, considering shallow-focus earthquakes appearance high probability, the new seismic action modeling method development becomes an actual problem.

Rayleigh waves are the main type of recorded waves at shallow earthquake that determines the need for taking them into account in the modeling of seismic vibrations of structures from earthquakes with little depth of the hypocenter. For combined longitudinal, shear and surface waves seismic action modeling the described below method is utilized: the velocity components v_x, v_z are defined at the vertical side surface of the elastic medium block, which further generate additionally the surface waves at the horizontal side of the massive block under investigation. For a number of unique features – the medium particles in the wave commit elliptical motion in the plane of the velocity vector and the normal to the surface, the amplitude of the oscillations decay exponentially with depth – determined that the generated surface wave is the Rayleigh wave.

4. Simulation of the dynamic behavior of the structure and its interaction with the soil under seismic influence

The simulation of the dynamic behavior of the structure and its interaction with soil has been modeled for two limiting cases of seismic source location: the horizontal and the vertical distance significant increase. The parallelepiped shaped elastic bodies based building models of several types were considered: buried (40x40 m foundation, 20 m heights, 8 m depth), weakly-buried (40x40 m foundation, 26 m heights, 2 m depth) and length-extended weakly-buried (100x20 m foundation, 10 m heights, 2 m depth). The computational domain of soil is also assumed a size of 1000×1000×500 m elastic parallelepiped. The materials mechanical characteristics: the building Young's modulus E = 21 GPa, the Poisson coefficient ν= 0.25, the density ρ= 900 kg/m^3, the ground Young's modulus E = 28 MPa, the Poisson coefficient ν = 0.3, the density ρ= 1887 kg/m^3. The contact interaction with a 0.3 friction coefficient is modeled between the building and soil. Boundary conditions for the seismic action from the bottom: the surface moves freely, side borders freely slide along the Oz axis, the velocity components v_x, v_z are defined at the lower boundary of soil. Boundary conditions for the seismic action at the side: the surface moves freely, the lower boundary is rigidly clamped, at one of the side surfaces were defined velocity components v_x, v_z, which further generate additionally surface waves on the surface of the soil. Kinematic conditions at the boundaries of the computational domain were determined by the method of [9], so that on the surface of the soil near the structures of reproducing accelerograms. Kinematic conditions at the boundaries of the computational domain were determined by the method of [9], in a way to satisfy on the surface of the soil near the structures accelerograms equivalence criteria.

The calculations allowed us to estimate the behavior of structures in the interaction with the soil for different lengths and depths structures and depending on the location of the source of seismic influence. Estimates of mutual displacements of the building walls and soil are presented in Table 1.

Table 1.The maximum building walls and soil mutual shifts.

Calculation model	Seismic impact source location	Maximum horizontal shift, mm		Maximum vertical shift, mm	
		Left side	Right side	Left side	Right side
Buried construction	Bottom	0,41	0,92	7,19	7,59
	Left	0,44	0,97	5,35	10,46
Weakly-buried construction	Bottom	1,83	3,36	11,2	4,8
	Left	2,39	7,53	11,9	10
Length-extended weakly-buried construction	Bottom	0,55	1,9	1,73	6,27
	Left	0,68	2,09	1,96	6,78

The analysis shows that the soil-structure interaction and its behavior are influenced by the earthquake source location in a different way, depending on the planned building size and depth of its underground part. The seismic action from the bottom lead to buried building significant swing, while the seismic action from the side causes significant swing of weakly-buried buildings. The maximum soil-structure mutual shifts were obtained for high weakly-buried construction for both analyzed variants of seismic action source location. The surface located earthquake sources lead to soil-structure mutual shifts increase at least on one side of structure, for all the construction types.

5. Conclusion

The deep foundation buildings connected with the underground pipeline combined seismic resistance analysis numeric method was proposed, which takes into account soil-structure contact interaction and the gravity forces impact. The numerical analysis of seismic vibrations of the construction and its interaction with soil was held for earthquake epicenter under the building and at a substantial distance location, which allow to create the most dangerous seismic loads action directivities. The computation results for two described limit cases allow estimating soil-structure interaction and behavior of structure for the earthquake source location of any kind. In calculations of structures on the horizontally propagating seismic effects should be considered depth of the hypocenter specific for the region.

The developed estimation method of the soil-structure dynamic interaction was applied for the seismic resistance estimation of the underground pipeline connected to the block of NPP: Busher (Iran), Novovoronezhskaya NPP-2, Kalininskaya, Rostovskaya NPP (Russia), Belorusskaya NPP (Belorussia) by request of JSC “NIAEP” (N Novgorod).

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