DOI 10.1007/s11204-022-09766-y
Soil Mechanics and Foundation Engineering, Vol. 58, No. 6, January, 2022 (Russian Original No. 6, November-December, 2021)

CONSTRUCTION UNDER SPECIAL SOIL CONDITIONS

CALCULATION OF BUILDING SETTLEMENT INDUCED BY DEEP EXCAVATION UNDER SEISMIC LOADING

UDC 624.131.542:624.159.14

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The present article describes a procedure for predicting the settlement of structures surrounding deep excavations in Vietnam that takes the technological settlement component into account. In this study, correction factors were established for a formula designed to calculate the excavation-induced settlement of buildings having strip foundations under seismic loading when factoring in the presence of soft saturated soils, which can be used in risk assessment during building operation. In addition, a developed procedure for determining the maximum force acting on a slurry wall taking seismic loading into account is presented. The calculation results obtained using the proposed procedure exhibited satisfactory consistency with those acquired as per EC8 and TCVN 9386-2012 (Vietnam). Finally, the comparison of predicted settlements with geotechnical monitoring data confirmed the possibility of applying the proposed procedure for calculating settlements.

Lying in a seismic zone, the territory of Vietnam is primarily comprised of soft saturated clay soils. In order to ensure the safety of buildings and civil engineering works affected by deep excavations under such challenging geotechnical conditions, the present authors developed procedures for predicting base settlement and calculating the forces that act on a slurry wall under seismic loading.

In the largest cities of Vietnam (Hanoi and Ho Chi Minh City), underground construction is complicated due to the presence of a high groundwater table (1.5 to 7.5 m from the surface), as well as man-made soils underlain by a layer of soft saturated soils (up to 30 m), which are comprised of clay soils and loose sands often containing organic matter; in some areas, these include layers of silt and peat. Negative factors include seismicity (7 and 8 points on the MSK-64 scale), the risk of disturbing the structure of soft clay soils, and the vibration liquefaction of saturated sands under dynamic and seismic loading, as well as the possibility of deep-excavation bottom heave causing water inflow.

Existing urban development is represented by 4–6-story buildings that include 1970–1980 panel buildings having shallow foundations and sometimes comprising pyramidal piles (up to 3.6 m in length), as well as new buildings having a pile-supported underground part using piles with lengths up to 65 m.

In order to develop an engineering approach for predicting base deformations, including under seismic loading, a typification of the geotechnical conditions applying to Hanoi and Ho Chi Minh City was performed. As a result, five types of geotechnical conditions (GTC) were identified, according to which the generalized physicomechanical characteristics of soils are indicated:

GTC-I: clays and soft-firm loams at 0–20 m (φ of 4 to 6°; c of 5 to 6 kPa; E of 1.1 MPa); from stiff to firm-stiff clays at 20–30 m (φ of 12 to 16°; c of 24 to 28 kPa; E of 4 MPa);

GTC-II: clays and soft-firm loams at 0–20 m (φ, c, and E – analogous to GTC-I); sandy loams (sometimes containing gravel) at 20–30 m (φ of 25 to 26°; c of 5.4 to 8.0 kPa);

GTC-III: sandy loams (sometimes containing gravel) at 0–40 m (φ of 23 to 26°; c of 5.4 to 7.5 kPa; E of 7 to 9 MPa);

Translated from Osnovaniya, Fundamenty i Mekhanika Gruntov, No. 6, November-December, 2021.

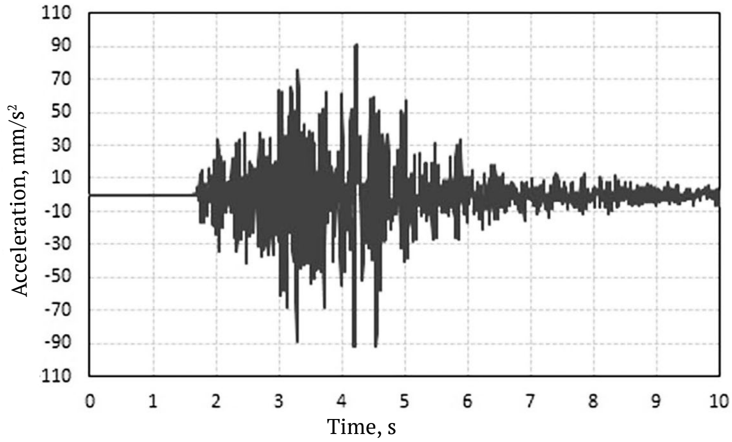

Fig. 1. Accelerogram of the 2001 earthquake in Dien Bien (Vietnam).

GTC-IV: very soft-stiff sandy loams and soft-firm loams at 0–10 m (φ of 7 to 14°; c of 14 to 21 kPa; E of 7 to 12 MPa); medium-density, fine, and medium sands at 10–20 m (φ of 32 to 34°; E of 5 to 28 MPa); soft-firm loams at 20–40 m (φ of 7 to 11°; c of 14 to 18 kPa; E of 15 to 28 MPa);

GTC-V: very soft-stiff sandy loams and soft-firm loams at 0–10 m (φ of 7 to 14°, c of 4 to 21 kPa, E of 7 to 12 MPa); from medium-density, fine to dense gravelly sands at 10–40 m (φ of 32 to 34°; E of 15 to 50 MPa).

The research involved an analysis of literature sources, numerical simulations, analytical calculations, as well as field observations of slurry wall displacements using inclinometers and geodetic measurement of deep excavation-induced building settlements.

Changes in the stress-strain state of a soil mass containing a deep excavation enclosed by a slurry wall and the foundations of neighboring buildings were analyzed via numerical simulation under drained and undrained conditions using the Mora-Coulomb soil model, the Hardening-Soil (HS) model, and PLAXIS 2D software. The HS undrained A model was found to provide the best agreement between the calculated and observed horizontal displacements of the slurry wall at the Hanoi site having a two-story underground section [1]. A close relationship between the measured and calculated surface subsidence parameters was also observed at the Hanoi site when using this model.

The HS undrained A model was applied in subsequent numerical experiments [1]. In order to establish deformation patterns in the soil mass containing a deep excavation enclosed by a slurry wall, a geotechnical simulation of changes in the stress-strain state of the soil mass was carried out under variable parameters: excavation depth H_k = 8–10 m, relative distance of the building from the deep excavation ($f_L = L/H_k$ of 0.0 to 1.5), restraining system type (reinforced concrete slabs 'Sl,' steel tube struts 'St,' and anchors 'A'); type of geotechnical conditions (GTC I–V). The slurry wall embedded to a depth of 23 m had a thickness of 0.8 m, as well as a pressure per unit length of q = 20 kN/m at the bottom of the strip foundation of the neighboring building.

The geotechnical simulation performed in PLAXIS 2D also factored in seismic loading using an accelerogram of the 2001 earthquake in Dien Bien (Fig. 1). This simulation was conducted using the schematics shown in Fig. 2.

Drawing on the method for calculating building settlement induced by deep excavation as per [2] and a series of numerical calculations, a formula for the settlement of surrounding structures was obtained. As required in risk assessment procedures, this formula factored in the lateral displacement of the slurry wall in soft saturated soils and seismic loading:

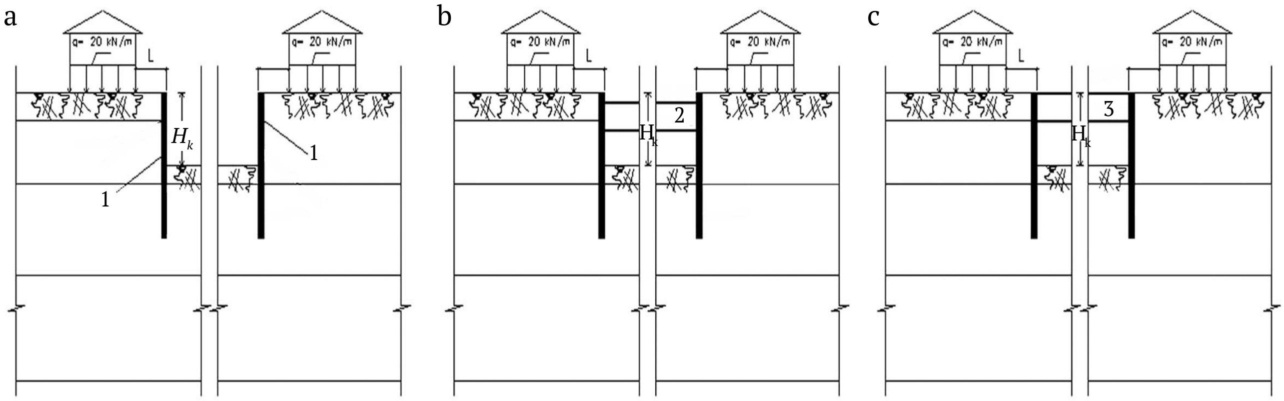

Fig. 2. Geotechnical model of the construction project involving restraining systems: a) anchors (1), b) steel tube struts (2), c) reinforced concrete slabs (H_k of 8 to 10 m).

TABLE 1

Type of a restraining system	Values of the coefficients k_s and k_r for GTCs				
	I	II	III	IV	V
'A'	*/*	2.5/3.2	2.7/1.2	2.6/2.3	2.7/1.5
'St'	2.9/1.0	1.8/1.0	2.1/1.0	2.5/1.0	1.7/1.0
'Sl'	2.4/0.7	1.7/0.9	1.9/0.8	2.3/0.8	1.7/0.7

Note. The values of k_s are given before the slash, with k_r values provided after it.
*The stability of the slurry wall is not ensured.

$$S_1(x)=k_r k's[k_{uv}k_s\delta_1\varphi(x)+q/k], \tag{1}$$

where $\delta_1=\dfrac{A_1 f_h H_k^5}{\alpha^4+A_1 H_k^4}$, $A_1=\dfrac{k}{EJ}$, $b=\dfrac{\alpha}{H_k}$, $\varphi(x)=[\Psi(\dfrac{b}{\lambda}-1)\eta_{\mathrm{II}}(\xi)+\eta_{\mathrm{IV}}(\xi)+e^{-b(x+L)}]$, $\Psi=\dfrac{b^2e^{(-bL)}}{2\lambda^2}$, $\eta_{\mathrm{II}}(\xi)=e^{(-\xi)}\cos\xi$, $\eta_{\mathrm{IV}}(\xi)=e^{(-\xi)}\sin\xi$, $\xi=\lambda x$, $\lambda=\sqrt[4]{k/4EJ}$, k is the coefficient of foundation subgrade reaction, q is the pressure at the strip foundation bottom of the building, k_r is the coefficient depending on the restraining system type, f_h is the empirical coefficient characterizing the maximum horizontal slurry wall displacement per the excavation depth, L is distance from the building to the excavation, H_k is the excavation depth, EJ is the stiffness of buildings varying in height, x is the coordinate of a point along the building length, $k_s = f_h^{\text{earthquake}}/f_h^{\text{no-earthquake}}$ is the coefficient determined the seismic effect on the horizontal slurry wall displacement (Table 1):

$$f_h^{no-earthquake}=\frac{u_h^{no-earthquake}}{H_k}, f_h^{earthquake}=\frac{u_h^{earthquake}}{H_k},$$

where $u_h^{\text{no-earthquake}}$ and $u_h^{\text{earthquake}}$ are maximum horizontal slurry wall displacements taking seismic loading into account and disregarding this loading, respectively, k_s' is a coefficient factoring in the type of the slurry wall restraining system under seismic loading; $k_{uv} = f_v/f_h$ is a coefficient (Table 2) factoring in the correlation between the horizontal slurry wall displacement and the maximum soil surface settlement around a deep excavation f_v – empirical coefficient characterizing the maximum soil surface settlement per the excavation depth; $f_v^{\text{no-earthquake}} = u_v^{\text{no-earthquake}}/H_k$, $f_v^{\text{earthquake}} = u_v^{\text{earthquake}}/H_k$, where $u_v^{\text{earthquake}}$ and $u_v^{\text{no-earthquake}}$ are maximum soil surface settlement with and without taking seismic loading into account.

TABLE 2

Type of a restraining system	Values of the coefficient *kuv* for GTCs				
	I	II	III	IV	V
no seismic loading					
‘A’	*/*	0.6/0.6	0.6/0.9	1.6/1.8	0.8/1.1
‘St’	1.2/1.7	0.9/0.9	0.7/0.9	0.7/0.4	0.9/0.7
‘Sl’	1.2/1.6	0.9/0.9	0.8/1.2	0.8/1.2	0.9/1.1
under seismic loading					
‘A’	*/*	0.6/–	1.0/1.0	1.0/1.5	0.9/1.2
‘St’	3.0/2.3	1.3/1.3	1.5/1.6	1.5/2.1	1.7/1.1
‘Sl’	–/1.6	1.7/1.6	1.7/1.9	1.8/2.1	2.0/2.6

Note. The values of k_{uv} at H_k = 8 m are given before the slash, with k_{uv} values at H_k= 10 m provided after it.
*The stability of the slurry wall is not ensured.

In order to determine the averaged coefficients k_r at H_k ranging from 8 to 10 m and f_L varying from 0.5 to 1.5, the maximum horizontal slurry wall displacements were compared for the three types of restraining systems (see Table 1):

$$k_r^{'St'} = 1,\ k_r^{'A'} = u_h^{'A'}/u_h^{'St'},\ k_r^{'Sl'} = u_h^{'Sl'}/u_h^{'St'},$$

where $u_h^{'A'}$, $u_h^{'St'}$, and $u_h^{'Sl'}$ are maximum horizontal slurry wall displacements.

The coefficient $k_s' = k_s^{(i)}/k_s^{'St'}$ depends on the type of the restraining system where the index (*i*) refers to reinforced concrete slabs or anchors, while ‘St’ denotes struts.

The analytically solved problem of a beam on an elastic foundation taking local elastic deformations into account was used to calculate the horizontal slurry wall displacements occurring at depth without factoring in seismic loading. The results indicate a satisfactory agreement with the data obtained via numerical simulation using Plaxis 2D.

The analytical calculations of the maximum force acting on the slurry wall under seismic loading employ the quasi-static method. A procedure for determining pressure applied to the slurry wall via the quasi-static method (specified in EC8) is also included in the Vietnamese standard TCVN 9386-2012. According to Russian standards, it is permitted to perform calculations for retaining walls taking seismic loading into account in the quasi-static or dynamic formulation using earthquake accelerograms.

The force applied to the retaining wall is determined as follows:

$$E_d = 1/2\gamma^*(1 \pm k_v)KH^2 + E_{ws} + E_{wd}, \quad (2)$$

where H is the wall height, E_{ws} is static water force, E_{wd} is dynamic water force; γ^* is unit weight of soil, K is the earth pressure coefficient (static and dynamic), and k_v is the earthquake coefficient.

The coefficient K can be calculated using the formulas from [3, 4]. Table 3 compares the results of analytical and numerical calculations of the maximum force acting on the slurry wall taking seismic loading into account:

$$\Delta_1 = [(E_d - E_{\text{Plaxis}})/E_{\text{Plaxis}}]\%. \quad (3)$$

The calculations indicate that the maximum forces acting on the slurry wall, as determined using analytical E_d and numerical E_{Plaxis} methods, differ by 4–20% depending on the GTC type.

TABLE 3

GTC	Restraining system of the excavation wall	Excavation depth (m)	E_d (kN/m)	E_{Plaxis} (kN/m)	Δ1 (%)
III	‘Sl’	8	560	538	3.99
II	‘Sl’	8	1079	885	18.04
V	‘Sl’	8	1124	1192	–5.7
V	‘Sl’	10	1401	1252	11.92
IV	‘A’	8	545	513	6.34

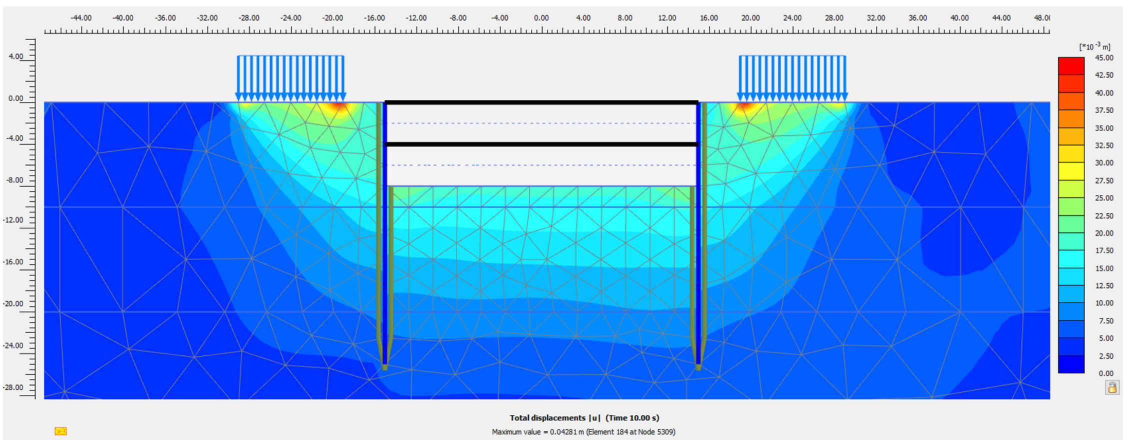

Fig. 3. Isofields of total soil displacement (GTC-V).

In order to determine the maximum force acting on the slurry wall for excavations measuring 8–10 m in depth taking into account seismic loading under the geotechnical conditions of Hanoi and Ho Chi Minh City, an empirical and analytical procedure was developed [5]. This procedure is based on numerical studies (Fig. 3), the calculation method given in [6], and the quasi-static method for determining the maximum force acting on a retaining wall under seismic loading.

Taking seismic loading into account, the maximum pressure applied to the slurry wall is calculated in accordance with:

$$E = E_1 + \Delta E_{1.\text{eq}} + \Delta E_{2.\text{eq}} - E_2, \tag{4}$$

$$E_1 = G_1 \tan\left(\alpha_1 - \varphi^1_{\text{avg}}\right) - \frac{c_1 l_1 \cos\varphi^1_{\text{avg}}}{\cos\left(\alpha_1 - \varphi^1_{\text{avg}}\right)}, \tag{5}$$

$$E_2 = G_2 \tan\left(\alpha_2 - \varphi^2_{\text{avg}}\right) - \frac{c_1 l_1 \cos\varphi_2}{\cos\left(\alpha_2 - \varphi^2_{\text{avg}}\right)}, \tag{6}$$

$$\Delta E_{1.eq} = G_1\left[K_h \pm K_v \tan\left(\alpha_1 - \varphi^1_{\text{avg}}\right)\right], \tag{7}$$

$$\Delta E_{2.eq} = G_2\left[K_h \pm K_v \tan\left(\alpha_2 - \varphi^2_{\text{avg}}\right)\right]. \tag{8}$$

The parameters of the schematic *B*1, *B*2, *H*1, *H*2, *L*1, *L*2, α_1, and α_2 presented in Fig. 4 were determined from the numerical calculations with the use of the Plaxis 2D program employing the isofields of soil displacements, which were obtained during a geotechnical simulation of seismic loading (see Fig. 3) using the accelerogram of the 2001 Dien Bien earthquake (see Fig. 1) [5].

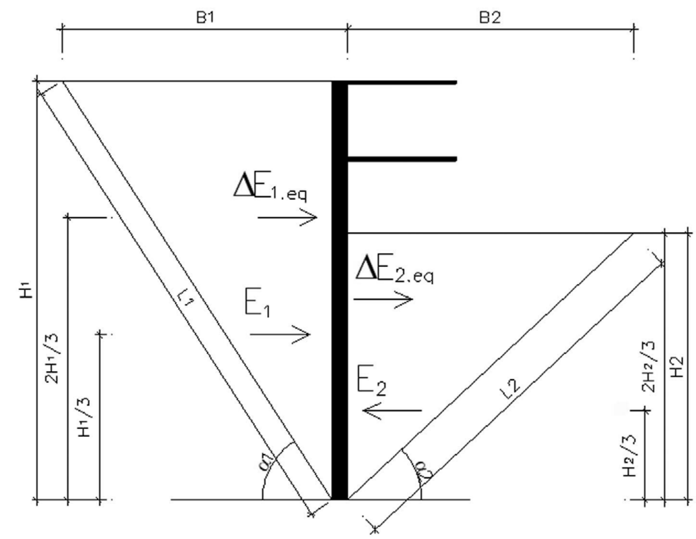

Fig. 4. Schematic for determining the maximum force acting on the slurry wall taking seismic loading into account.

TABLE 4

Construction project	Maximum settlement, mm				Discrepancy between $S(x)$ and S_{meas}
	$S_1(x)$ as per (1)	$S_2(x)$ as per (11)	$S(x)$ as per (10)	S_{meas}	
Building in Hanoi	9.8	6.2	16.0	14.0	12%
Hotel in Ho Chi Minh City	10.9	12.1	23.0	22.5	2.2%
Saigontourist (Ho Chi Minh City)	8.6	7.1	15.7	11.4	27.4%
Trade Center (Ho Chi Minh City)	7.1	8.8	15.9	12.7	25.2%

The weighted average friction angles in the active earth pressure φ^1_{avg} and passive earth pressure zones φ^2_{avg} are determined as follows:

$$\varphi_{avg} = \frac{\sum \varphi_i h_i}{\sum h_i}, \tag{9}$$

where h_i is the thickness of the ith soil layer extending to the depth H_1 (m).

The calculations of the maximum force acting on the slurry wall under seismic loading performed using the proposed procedure differ from the results obtained as per EU8 and TCVN 9386-2012 by 4–25 % and from those obtained via numerical methods by 7–12 % (Table 4).

Deep excavation induced settlement of a building along its length is determined as follows, taking the slurry wall construction process into account:

$$S(x) = S_1(x) + S_2(x), \tag{10}$$

where $S_1(x)$ is a settlement determined according to (1), $S_2(x)$ is a settlement determined as per [7]:

$$S_2(x) = -\alpha A' e^{B' L(x)}, \tag{11}$$

where A' and B' are coefficients that depend on the geometric parameters of the slurry wall section, slurry density, and soil conditions, e is the Euler's constant, $L(x)$ is a distance from the slurry wall to a point along the building length, α is a correction factor amounting to 1.3.

In Ho Chi Minh City, the excavation of an underground structure constructed according to the top-down method was located next to a hotel, Saigontourist, and a shopping mall. At the time of the comparison, the excavation depth reached 8 m.

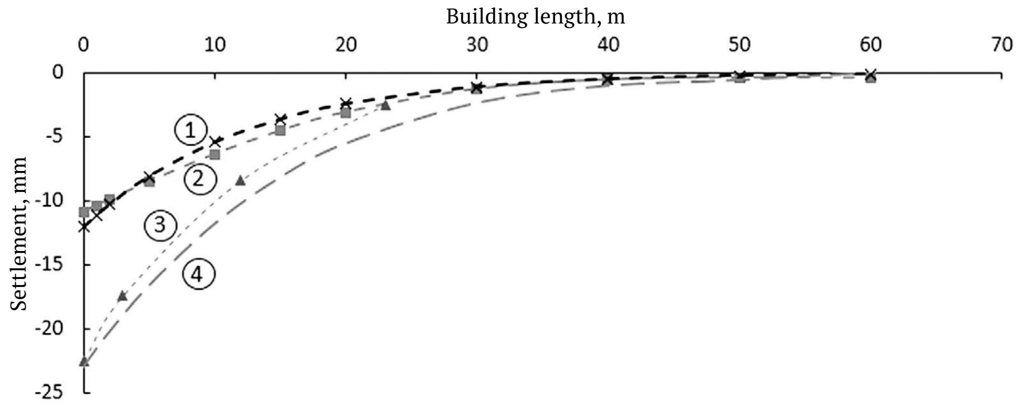

Fig. 5. Graphs of the calculated (taking the technological component into account) and measured settlements along the hotel length in Ho Chi Minh City: 1) technological settlement (as per Eq. (11)), 2) calculated settlement (as per Eq. (1)), 3) measured settlement S_{meas}, and 4) settlement calculated taking the technological component into account (as per Eq. (10)).

In order to verify Eq. (10), the calculated settlements were compared with the data obtained from the geotechnical monitoring of sites having an underground part in Ho Chi Minh City and Hanoi without seismic loading.

The calculated settlement exceeded the measured value by 2–27%.

Figure 5 presents the graphs of settlements calculated for the hotel in Ho Chi Minh City as an example.

Conclusions

Correction coefficients were obtained for the formula designed to calculate building settlements induced by deep excavations, taking into account the presence of soft saturated soils and seismic loading.

A method for determining the maximum force acting on a slurry wall in excavations having a depth of 8–10 m under the geotechnical conditions of Hanoi and Ho Chi Minh City was developed taking seismic loading into account. The calculation results show a good agreement with the values obtained as per EC8 and TCVN 9386-2012 (Vietnam).

By comparing the measured building settlements affected by deep excavation at the sites in Hanoi and Ho Chi Minh City with those calculated using the proposed procedure, its application is validated for the considered geotechnical conditions, which are typical for Vietnam.

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