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Upheaval deformations of ground induced by expansive soils and application to site assessment
膨胀土引起的地面上抬变形及在场地评估中的应用

Omer E. M. FADOL(区　马) , ZHANG Ke-xu(张克绪)
(School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China)

Abstract: In this paper, the methods of prediction of upheaval deformations of ground induced by expansive soils and the assessment of site including expansive soil layers are reviewed. A method of prediction of the upheaval deformations on the basis of soil softening is formulated. Relationships to determine swelling potential of soil element in half-space under self weight are presented. The computation method of upheaval deformations on horizontal ground including expansive soil layers is explained in details. A site including expansive soil layer with high swelling pressure is chosen to illustrate the influence of thickness and position of expansive soil layer on upheaval deformations. Finally, the computation method of upheaval deformations of ground is applied to assessment of sites including expansive soil layers, and important influence of thickness and position of expansive soil layer on site assessment is shown.

Key words: expansive soils; swelling potential; upheaval deformations on ground; softening model; site assessment.
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Biography: Omer E. M. FADOL(1962-) , male, Sudanese, lecturer, doctor candidate, majored in geotechnical engineering.

摘　要: 回顾了预示膨胀土引起的地面上抬变形的方法和含膨胀土层场地的评估。基于软化模型提出了一个地面上抬变形的计算方法及其公式。给出了确定半空间无限体中土单元在自重下的膨胀势的关系式。对该含膨胀土层的水平场地的地面上抬变形计算方法做了详细说明。对一个含高膨胀压力的膨胀土层的场地计算了地面上抬变形,以说明膨胀层位置及厚度对地面上抬变形的影响。最后,将该地面上抬变形方法应用于含膨胀土层场地的评估,并以例显示了膨胀土层厚度和位置对场地评估的重要影响。

关键词: 膨胀土; 膨胀势; 地面上抬变形; 软化模型; 场地划分

0　Introduction*

Many assessment schemes provide an 'expansion rating' to qualitatively assess the degree of probable expansion. Expansion ratings may be something as 'high,' 'medium', and 'low', or 'critical' and 'non critical'[1].

Some of these assessment methods are using engineering index properties, i. e., unified soil classification system (USCS)[2]; clay content, plasticity index, and shrinkage limit[3,4]; clay content, liquid limit, and standard penetration blows[5]; and plasticity index method[6]. An assessment scheme which combines index properties with cation- exchange capacity is also available[7].

Several different procedures for predicting volume changes or swelling pressures of expansive soils exist[10,11]. Heave can be predicted using oedometer test generally[8,9]. Total heave is the sum of the displacements in each soil layer, that is,

$$\rho = \sum_{i=1}^{n} \frac{\Delta e_i}{(1+e_0)_i} z_i, \tag{1}$$

where ρ is the total heave; z_i is the initial thickness of layer i; Δe_i is the change of void ratio of layer i following absorption of water; e_0 is the initial void ratio of layer i; n is the number of layers.

According to the Chinese Code[13], deformations of expansive soils are calculated by the following formula:

$$S_c = \sum_{i=1}^{n} (\delta_{epi} + \lambda_{si}\Delta w_i) h_i, \tag{2}$$

where δ_{epi} is the expansion ratio of soil layer i under pressure p_i which is stipulated as 50 kPa; λ_{si} is the linear shrinkage coefficient of soil layer i; h_i is the thickness of soil layer i; Δw_i is the average value of allowable water content change in soil layer i during shrinkage; n is the number of soil layers.

It is important to take into account the fact that two soils may have the same swelling potential, but exhibit very different amounts of swell[12]. It may be due to the different positions and thicknesses of the expansive soil layers in sites.

It is known from the above review that the position of expansive soils layers in site is not taken into account, in which we believe that it has important impact in site assessment. In this paper, upheaval deformations of ground induced by expansive soils will be formulated using a mechanical model based on the softening of expansive soil.

1　Softening model

Following absorption of water, expansive soils are softening and additional compression is induced. Based on such a concept a mechanical model to determine swelling potential of expansive soils will be introduced.

1.1　Basic relationships

A relationship between swelling strain (ε_{ve}) following absorption of water and vertical stress (σ_{v0}) is shown in Fig. 1[6]. In the figure ε_{ve0}, ε_{ve} are the swelling strains under free load and under load respectively, $\Delta\varepsilon_{vc}$ is the ad-

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ditional compression strain induced by softening, and P_{ev} is swelling pressure.

From Fig. 1 we get

$$\Delta\varepsilon_{vc} = \varepsilon_{ve0} - \varepsilon_{ve} \tag{3}$$

Let

$$\Delta\varepsilon_{vc} = \frac{\sigma_{v0}}{\bar{E}_c}, \tag{4}$$

where $\bar{E}_c$ is the additional compression modulus. Substituting Eq. (4) into Eq. (3) and rearranging, we get:

$$\varepsilon_{ve} = \varepsilon_{ve0} - \frac{\sigma_{v0}}{\bar{E}_c}. \tag{5}$$

From Fig. 1 it is found out that the relationship between $\Delta\varepsilon_{vc}$ and σ_{v0} is nonlinear. Hence $\bar{E}_c$ depends on vertical stress σ_{v0}.

When $\sigma_{v0} = P_{ev}$ then $\varepsilon_{ve} = 0$, from Eq. (5) we get:

$$\varepsilon_{ve0} = \frac{P_{ev}}{\bar{E}_{cP}}, \tag{6}$$

in which $\bar{E}_{cP}$ is the additional compression modulus according to swelling pressure (P_{ev}). Substituting Eq. (6) into Eq. (5) yields:

$$\varepsilon_{ve} = \frac{P_{ev}}{\bar{E}_{cP}} - \frac{\sigma_{v0}}{\bar{E}_c}. \tag{7}$$

1.2 Determination of $\bar{E}_c$

We can determine $\bar{E}_c$ by test data. From Eq. (5) we have:

$$\bar{E}_c = \frac{\sigma_{v0}}{\varepsilon_{ve0} - \varepsilon_{ve}}, \tag{8}$$

where ε_{ve0}, ε_{ve} and σ_{v0} are known from test data.

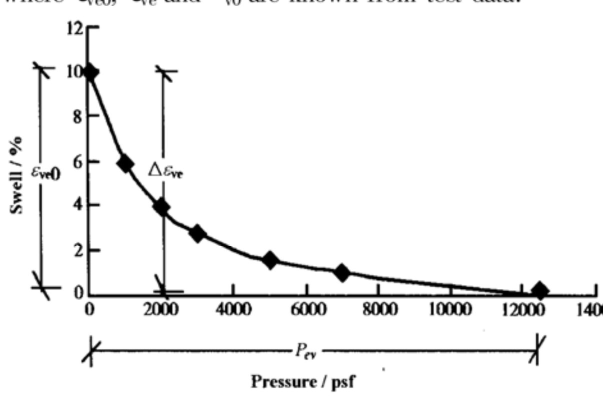

Fig. 1 Pressure- swell relationship[6]

Using the test data in Fig. 1, it is found out that the relation of $\bar{E}_c$ and σ_{v0} is linear, as shown in Fig. 2. English Units are used in the source data, so it is introduced here without conversion into International Units. The relationship can be represented by a linear function as follows:

$$\bar{E}_c = a\sigma_{v0} + b, \tag{9}$$

where a, b are the model parameters which can be determined from Fig. 2. For the data shown in Fig. 1, $a = 8.8$ and $b = 15437.24$.

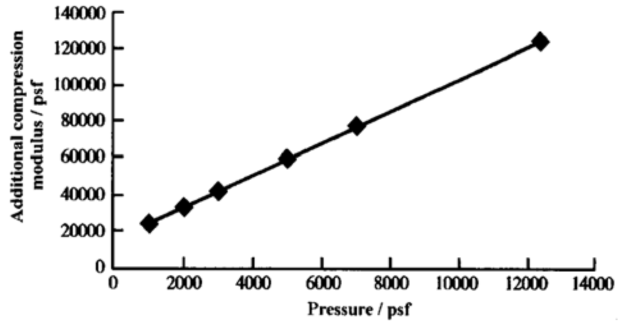

Fig. 2 Pressure- additional compression modulus relationship

2 Swelling potential of soil elements in half space under self weight

In this case soil element is in K_0 state. Normal stresses σ_{x0}, σ_{y0} and σ_{z0} occur on soil element due to the self weight of soils and

$$\sigma_{x0} = \sigma_{y0} = K_0\sigma_{z0}. \tag{10}$$

There is only vertical strain in soil element in K_0 state; here K_0 is the coefficient of static earth pressure. If swelling strain under free load (ε_{ve0}) is confined completely there must be a vertical expansion stress (P_{ez}) exerting on soil elements, and result in horizontal stresses:

$$P_{ex} = P_{ey} = K_0 P_{ez}, \text{ and } P_{ez} = P_{ev}. \tag{11}$$

Because soil elements are in K_0 state, then

$$\varepsilon_{ze0} = \varepsilon_{ve0}, \text{ and } \varepsilon_{xe0} = \varepsilon_{ye0} = 0, \tag{12}$$

in which ε_{ze0}, ε_{xe0} and ε_{ye0} are the normal strains in Z, X, Y directions, respectively.

According to the softening model, additional compressive strains occur under the self weight stresses σ_{x0}, σ_{y0} and σ_{z0}. Let $\Delta\varepsilon_{xc0}$, $\Delta\varepsilon_{yc0}$ and $\Delta\varepsilon_{zc0}$ be the additional compressive strains in X, Y, Z directions respectively, since soil element is in K_0 state, then

$$\Delta\varepsilon_{xc0} = \Delta\varepsilon_{yc0} = 0, \ \Delta\varepsilon_{zc0} = \Delta\varepsilon_{vc} = \frac{\sigma_{z0}}{\bar{E}_c}. \tag{13}$$

Thus, the total expansive strain of soil in three directions in the K_0 state is as follows:

$$\varepsilon_{xe} = \varepsilon_{ye} = 0, \tag{14}$$

$$\varepsilon_{ze} = \varepsilon_{ze0} - \Delta\varepsilon_{zc0} = \frac{P_{ev}}{\bar{E}_{cP}} - \frac{\sigma_{z0}}{\bar{E}_c}. \tag{15}$$

Eq. (15) represents the swelling potential of soil elements in half-space under self weight.

3 Calculation method of upheaval deformations of ground on level site including expansive soil layers

The notations used in the following equations are shown in Fig. 3. The value of upheaval deformations on ground induced by expansive soil layers following absorption of water can be calculated by the following formula:

$$S_u = \sum_{i=1}^{n} \varepsilon_{ze} \Delta Z_i, \qquad (16)$$

or

$$S_u = \sum_{i=1}^{n} \left(\frac{P_{ev}}{\bar{E}_{cP}} - \frac{\sigma_{z0i}}{\bar{E}_{ci}} \right) \Delta Z_i, \qquad (17)$$

where $\bar{E}_{ci}$ is the additional compression modulus of layer i derived from the softening model; $\bar{E}_{cP}$ is the additional compression modulus according to the swelling pressure; S_u is the upheaval deformation on ground of site with expansive soil layers; ΔZ_i is the thickness of soil layer i; σ_{z0i} is the vertical stress of central point of soil layer i; n is the number of sub layers.

4 Influence of position and thickness of expansive soil layers on upheaval deformations

Unlike general settlement prediction, the heave estimate depends on many factors which cannot be readily determined[1,6], such as climate, the depth to water table, the nature and degree of desiccation of the soil, and extraneous influence.

Various methods to predict the amount of total heave have limitations[6]. The influence of the position of expansive soils layer is not emphasized in these methods. We believe that it has important impact on the upheaval deformations and, hence, site assessment. The deeply seated expansive soil layers can exhibit less upheaval deformations than shallower seated ones due to weight of overburden layers. In qualitative and quantitative assessment of the degree of probable expansion the position of expansive soil layer must be considered.

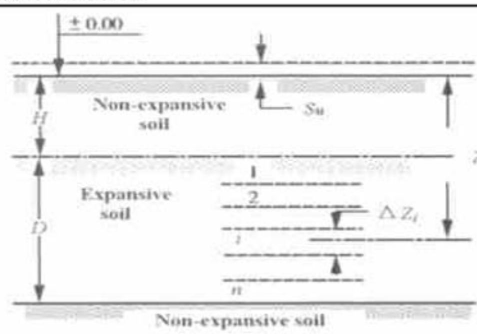

Fig. 3 Section through level site including expansive soil layers

For illustration of the influence, a site including expansive soil layer with high swelling pressure is chosen. Parameters used for the site are shown in Table 1. The maximum depth of active zone equals the depth of water table while the minimum equals the depth of the seasonal moisture content fluctuations. Let H, D be position and thickness of expansive soil layer respectively. H is taken between 0 and 3.5 m and D is taken between 0.5 and 4 m. Active zone depth equals $H + D$, and $(H + D)_{max} = 7.5$ m. The model parameters a, b are 8.8 and 15437.24, respectively, which are determined above.

Table 1 The parameters used for the site of high swelling pressure

Soil layer	Thickness Range/ m	Density / (kN·m^{-3})	Swelling pressure / kPa
Non-expansive	0~ 3.5	17.5	—
Expansive	0.5~ 4	17.5	593.7*

(*) This value is converted from English Units[6].

Eq. (17) is used to calculate the upheaval deformations related to the position and thickness of expansive soil layer in the site. The results are shown in Fig. 4. It is found out from the figure that upheaval deformations are greatly influenced by the positions and thicknesses of expansive soil layers. The upheaval deformations of ground decrease with deeper position of expansive soil layer and increase with the increase of soil layer thickness.

5 Application to site assessment including expansive soil layers

According to the results obtained above, a reasonable method of site assessment must consider three factors of site conditions, i.e. swelling pressure, position and thickness of expansive soil layers in site. In addition, damage to structure induced by expansive soils is related to ground deformation closely. Hence ground deformations can be used as a quantitative index to assess influence of expansive soil included in a site. A criterion in Table 2 is adopted in Chinese Code to assess site including expansive soil layers[13], which is based on deformation of ground. The deformations of ground include two parts: shrinkage deformation and swell deformation.

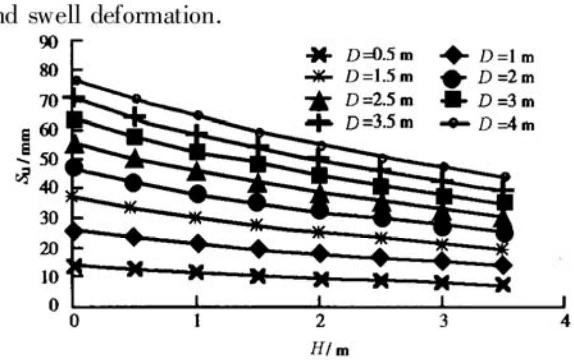

Fig. 4 Upheaval deformations(S_u) related to position (H) and thickness (D) of expansive soil layers for sites of high swelling pressures

Because the method presented in this paper can consider the influence of swelling pressure, position and thickness of expansive soil layers on upheaval deformation of ground, the method can be used to calculate the swell deformation part. The condition of position and thickness of expansive soil layers adopted in Fig. 4 can be considered as general case. From the results in Fig. 4, it is shown that upheaval deformation of ground can be varied, about, from 10 mm to 80 mm due to the impact of position and thickness of expansive soil layers in general case. With the criteria in Table 2, the range of upheaval deformation of ground is larger than the deformation range of ground from very low to high site classification. Thus, if a site is only assessed by upheaval deformation of ground, the site can be classified as very low, low, medium, or high, depending on the position and thickness of expansive soil layers in the site. Hence, it is necessary to consider the position and thickness of expansive soil layers in assessment of site including expansive soil layers.

Table 2 Deformation criteria for assessment of site including expansive soil layers[13]

Deformation, S / mm	Classification
$\geqslant 70$	High
$35 \leqslant S < 70$	Medium
$15 \leqslant S < 35$	Low
< 15	Very Low

6 Conclusions

From the above study the following conclusions are drawn:

(1) Upheaval deformations induced by expansive soils can be formulated on the basis of soil softening model.

(2) Upheaval deformations are greatly influenced by the position and thickness of expansive soil layers, which decrease with deeper positions, and increase with the increasing thickness of expansive soil layers.

(3) The method of computation of upheaval deformation can be used to calculate the swell part of ground deformation of the criterion in Table 2.

(4) Qualitative and quantitative assessment of the free level site including expansive soil layers is considerably changed from high to medium, low, and very low because of the influence of position and thickness of expansive soil layers.

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关于举行《’04 全国建筑基桩检测技术高级研讨班》的通知(第 1 号)

由中国科学院武汉岩土力学研究所、铁道第二勘察设计院工程测试中心、湖北•武汉无损检测学会联合发起与组织的《’04 全国建筑基桩检测技术高级研讨班》拟于 2004 年 9 月 28 日~ 10 月 4 日在成都举行。内容包括: ①基桩高、低应变的测试技术; ②《建筑基桩检测技术规范》的宣传贯彻; ③测试新技术。会务联系人: 李祺、刘明贵; 通讯地址: 武汉市武昌区小洪山中国科学院武汉岩土力学研究所, 邮政编码: 430071, 传真: 027 - 87198699; 电话: 027 - 87199304 - 805、13907100573, 电子信箱: rsm@whrsm.ac.cn。

(中国科学院武汉岩土力学研究所 供稿)