DOI: 10.13476/j.cnki.nsbdqk.2016.05.023
胡晓军, 吴延枝. 非饱和膨胀土主动土压力的库仑解析解[J]. 南水北调与水利科技, 2016, 14(5): 146-149, 156. HU Xiao-jun, WU Yan-zhi. Coulomb analytic solution of active earth pressure for unsaturated expansive soils[J]. South-to-North Water Transfers and Water Science & Technology, 2016, 14(5): 146-149, 156. (in Chinese)

# 非饱和膨胀土主动土压力的库仑解析解

胡晓军, 吴延枝

(合肥学院 建筑工程系, 合肥 230601)

摘要: 分析非饱和膨胀土的强度特性, 考虑非饱和膨胀土含水量与强度的关系及相关影响因素, 基于平面滑裂面假设, 运用库仑理论, 推得了计算非饱和膨胀土主动土压力的解析解公式, 并用实际算例对公式进行检验。算例分析表明, 随着含水量的增加, 主动土压力增大, 其变化幅度逐渐减小; 若不考虑含水量的影响, 结果偏于保守; 应用本文建立的解析解公式, 可直接得出膨胀土的主动土压力及填土滑裂面与水平面的夹角。

关键词: 非饱和膨胀土; 含水量; 基质吸力; 主动土压力; 库仑解析解

中图分类号: TU443 文献标志码: A 文章编号: 1672-1683(2016)05-0146-04

## Coulomb analytic solution of active earth pressure for unsaturated expansive soils

HU Xiao-jun, WU Yan-zhi

(*Department of Civil Engineering, Hefei University, Hefei 230601, China*)

**Abstract:** The strength characteristics of unsaturated expansive soil was analyzed, based on the plane sliding surface assumption, the analytical formula of the active earth pressure calculation for unsaturated expansive soil was proposed which considered the relationship between water content and strength of unsaturated expansive soil and other relevant factors, using the basic principle of Coulomb theory, and practical example was used to validate the formula. The example showed that the active earth pressure increased with the increase of moisture, while the magnitude of the change decreased; If the influence of water content was not considered, the result was conservative; The active earth pressure of expansive soil and the angle of filling sliding surface with the horizontal could be obtained directly applying the method established in this study.

**Key words:** unsaturated expansive soil; moisture; matric suction; active earth pressure; Coulomb analytic solution

膨胀土是一种具有裂隙性、胀缩性和超固结性的高塑性黏土, 当含水率发生变化时, 会遇水膨胀、失水收缩, 表现出明显的胀缩性[1]。膨胀土在世界六大洲的40多个国家均有分布。我国先后在20多个省市发现有膨胀土[2]。工程建设中经常会遇到膨胀土的问题。膨胀土的强度与含水量关系密切, 且土压力又与填土强度密切相关, 因而膨胀土的土压力应充分考虑含水量变化的影响。目前, 非饱和土主动土压力的研究主要集中在以朗肯理论为基础土压力计算方法研究[3-10], 而库仑土压力的研究较少。众所周知朗肯理论的假定条件比较苛刻, 严格满足其条件的工程情况较少。库仑土压力则能适应更多形式的挡墙和填土, 具有广泛的适用范围。赵均海[11]基于非饱和土双应力状态变量抗剪强度统一解, 得到了非饱和土库仑主动土压力统一解, 但公式不能反映土压力与含水量之间的关系; 朱志铎[12]

收稿日期: 2015-11-12 修回日期: 2016-07-07 网络出版时间: 2016-08-18
网络出版地址: http://www.cnki.net/kcms/detail/13.1334.TV.20160818.2130.013.html
基金项目: 安徽高等学校省级自然科学研究重点项目(KJ2011Z320); 合肥学院土木工程重点学科建设项目(2014xk04)
**Fund:** Provincial key Projects of Natural Science Research for Colleges and Universities in Anhui(KJ2011Z320); Key disciplines of civil engineering of Hefei University(2014xk04)
作者简介: 胡晓军(1966-), 男, 安徽当涂人, 教授, 博士, 主要从事岩土力学方面研究。E-mail: ahsdxyhxj@163.com

考虑非饱和土基质吸力,基于库仑理论,建立了非饱和膨胀土的主动土压力公式,但求解过程必须进行试算,较为繁琐;胡晓军[13]在库仑精确解的基础上,导出了非饱和膨胀土极值条件下的库仑主动土压力公式,但公式较为复杂,在实际工程中应用较为困难。本文在相关研究的基础上,考虑非饱和膨胀土含水量与强度的关系等相关影响因素,得到了非饱和膨胀土库仑主动土压力计算的解析式,应用该公式,可直接得出主动土压力及填土滑裂面与水平面的夹角。

## 1 膨胀土主动土压力公式的建立

### 1.1 非饱和膨胀土的强度

针对非饱和土强度,国内外学者开展了大量研究工作,其中代表性的成果为 Fredlund 建立的非饱和土的双变量强度表达式[14]。本文土压力计算采用该强度公式,其表达式为:

$$\tau_f = c' + (\sigma - u_a)\tan\varphi' + (u_a - u_w)\tan\varphi^b \qquad (1)$$

式中:$c'$ 为有效凝聚力;$u_a$ 为孔隙气应力;$u_w$ 为孔隙水应力;$(u_a - u_w)$ 为基质吸力;$\varphi'$ 为有效内摩擦角;$\varphi^b$ 为吸力摩擦角(基质吸力的函数,根据工程中常遇到的吸力范围,可将其作为常数[15]);$c' + (u_a - u_w)\tan\varphi^b$ 为等效凝聚力。

对于非饱和膨胀土,吸力和含水量关系,可用下式表示[15]:

$$\lg u_s = -m \times \lg\omega + n \qquad (2)$$

式中:$u_s$ 为基质吸力,即$(u_a - u_w)$;$\omega$ 为含水量;$m$、$n$ 为常数,由试验确定。

### 1.2 主动土压力公式的建立

如图 1 所示挡土墙,设当墙体发生离开填土的位移,填土的抗剪强度全部发挥时,填土上部出现拉裂缝深度为 $Z_0$,形成图示 AA, BCG 的滑动体。$Z_0$ 可用下式求出[13]:

$$Z_0 = \frac{2(c' + u_s\tan\varphi^b)}{\gamma\tan(45° - \dfrac{\varphi'}{2})} - \frac{q}{\gamma} \qquad (3)$$

式中:$\gamma$ 为填土的天然重度、$q$ 为填土表面超载;$u_s$ 可用(2)式求出;当 $Z_0 \leqslant 0$ 时,填土表面无裂缝开展,取 $Z_0 = 0$。

对滑动土体进行受力分析,作用力有以下 5 项。

(1) 土体自重 $W_1$、$W_2$ 及 $q$ 的合力 $W_3$,由几何关系得:

$$W_1 = \frac{1}{2}\gamma h^2\,\frac{\cos(\alpha - \beta)\cos(\theta - \alpha)}{\cos^2\alpha\sin(\theta - \beta)} \qquad (4)$$

$$W_2 = \gamma Z_0 h\,\frac{\cos\beta\cos(\theta - \alpha)}{\cos\alpha\sin(\theta - \beta)} \qquad (5)$$

$$W_3 = qh\,\frac{\cos\beta\cos(\theta - \alpha)}{\cos\alpha\sin(\theta - \beta)} \qquad (6)$$

(2) $BC$ 上的反力 $R$;

(3) $BC$ 上的总黏聚力 $C = (c' + u_s\tan\varphi^b)\,h \cdot \dfrac{\cos(\alpha - \beta)}{\cos\alpha\sin(\theta - \beta)}$;

(4) 墙背 $AB$ 上的总黏着力 $C_w = c_w\,\dfrac{h}{\cos\alpha}$;

(5) 墙背 $AB$ 上的反力 $E$。

式中:$h = H - Z_0$;$H$ 为挡土墙的高度;$\delta$ 为填土与墙背的外摩擦角;$c_w$ 为填土与墙背接触面上的单位黏着力。

上述的 5 个力形成闭合力矢多边形(图 2),其中矢量 $fc$ 为土压力 $E$。过 $c$ 点作 $ch$ 平行于 $ag$,交 $gf$ 于 $h$,延长 $hc$ 交过 $b$ 点平行于 $fc$ 的平行线于点 $d$,延长 $fc$ 交 $ag$ 于点 $i$,过点 $h$ 作 $hi'$ 平行于 $fc$ 交 $ag$ 于 $i'$ 点。

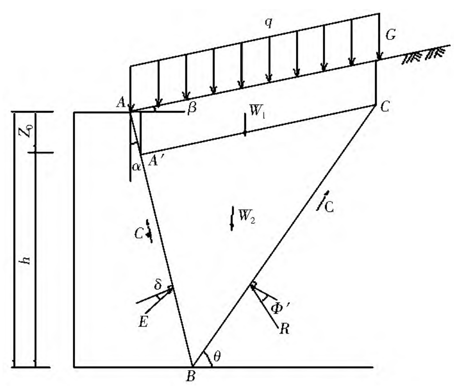


图 1 挡土墙与滑动土体

Fig. 1 Retaining wall and sliding wedge

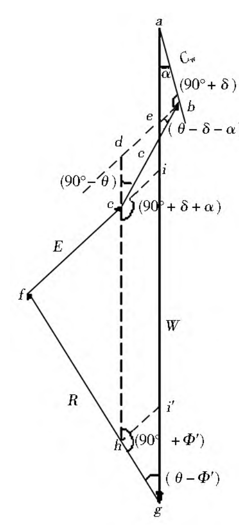


图 2 挡土墙土压力计算

Fig. 2 Earth pressure calculation on Retaining wall

由图中可见:

$$\overline{ch}=\overline{ag}-\overline{ae}-\overline{dc}-\overline{ig} \tag{7}$$

$$\overline{ag}=W_1+W_2+W_3=\left[\frac{1}{2}\gamma h^2\frac{\cos(\alpha-\beta)}{\cos^2\alpha}+\frac{\gamma Z_0h\cos\beta}{\cos\alpha}+\frac{qh\cos\beta}{\cos\alpha}\right]\cdot\frac{\cos(\theta-\alpha)}{\sin(\theta-\beta)} \tag{8}$$

由图 2 中的几何关系得:

$$\overline{ae}=\frac{c_wh\cos\delta}{\cos\alpha\cos(\alpha+\delta)} \tag{9}$$

$$\overline{dc}=\frac{(c'+u_s\tan\phi)h\cos(\alpha-\beta)}{\cos\alpha\cos(\alpha+\delta)}\cdot\frac{\sin(\theta-\alpha-\delta)}{\sin(\theta-\beta)} \tag{10}$$

$$\overline{ig}=\frac{(c'+u_s\tan\phi)h\cos(\alpha-\beta)}{\cos\alpha\cos(\alpha+\delta)}\cdot\frac{\cos\theta\cos(\theta-\alpha-\delta-\phi)}{\sin(\theta-\beta)\sin(\theta-\phi)}-\frac{c_wh\cos\alpha}{\cos\alpha\cos(\alpha+\delta)}\cdot\frac{\cos(\theta-\alpha-\delta-\phi)}{\sin(\theta-\phi)} \tag{11}$$

将式(8)-式(11)带入式(7)得:

$$\overline{ch}=\left[\frac{1}{2}\gamma h^2\frac{\cos(\alpha-\beta)}{\cos^2\alpha}+\frac{\gamma Z_0h\cos\beta}{\cos\alpha}+\frac{qh\cos\beta}{\cos\alpha}\right]\cdot\frac{\cos(\theta-\alpha)}{\sin(\theta-\beta)}-\frac{c_wh\cos\delta}{\cos\alpha\cos(\alpha+\delta)}-\frac{(c'+u_s\tan\phi)h\cos(\alpha-\beta)}{\cos\alpha\cos(\alpha+\delta)}\cdot\frac{\sin(\theta-\alpha-\delta)}{\sin(\theta-\beta)}-\frac{(c'+u_s\tan\phi)h\cos(\alpha-\beta)}{\cos\alpha\cos(\alpha+\delta)}\cdot\frac{\cos\theta\cos(\theta-\alpha-\delta-\phi)}{\sin(\theta-\beta)\sin(\theta-\phi)}+\frac{c_wh\sin\alpha}{\cos\alpha\cos(\alpha+\delta)}\cdot\frac{\cos(\theta-\alpha-\delta-\phi)}{\sin(\theta-\phi)} \tag{12}$$

又三角形 $hfc$ 中应用正弦定理可得:

$$E=\overline{ch}\frac{\sin(\theta-\phi)}{\cos(\theta-\alpha-\delta-\phi)} \tag{13}$$

将(12)式带入式(13)得:

$$E=\left\{\left[\frac{1}{2}\gamma h^2\frac{\cos(\alpha-\beta)}{\cos^2\alpha}+\frac{\gamma Z_0h\cos\beta}{\cos\alpha}+\frac{qh\cos\beta}{\cos\alpha}\right]\cdot\frac{\cos(\theta-\alpha)}{\sin(\theta-\beta)}-\frac{c_wh\cos\delta}{\cos\alpha\cos(\alpha+\delta)}-\frac{(c'+u_s\tan\phi)h\cos(\alpha-\beta)}{\cos\alpha\cos(\alpha+\delta)}\cdot\frac{\sin(\theta-\alpha-\delta)}{\sin(\theta-\beta)}-\frac{(c'+u_s\tan\phi)h\cos(\alpha-\beta)}{\cos\alpha\cos(\alpha+\delta)}\cdot\frac{\cos\theta\cos(\theta-\alpha-\delta-\phi)}{\sin(\theta-\beta)\sin(\theta-\phi)}+\frac{c_wh\sin\alpha}{\cos\alpha\cos(\alpha+\delta)}\cdot\frac{\cos(\theta-\alpha-\delta-\phi)}{\sin(\theta-\phi)}\right\}\cdot\frac{\sin(\theta-\phi)}{\cos(\theta-\alpha-\delta-\phi)} \tag{14}$$

化简得:

$$E=\left[\frac{1}{2}\gamma h^2\frac{\cos(\alpha-\beta)}{\cos^2\alpha}+\frac{(q+\gamma z_0)h\cos\beta}{\cos\alpha}\right]\cdot\frac{\cos(\theta-\alpha)\sin(\theta-\phi)}{\sin(\theta-\beta)\cos(\theta-\alpha-\delta-\phi)}-\frac{(c'+u_s\tan\phi)h\cos(\alpha-\beta)\cos\phi}{\cos\alpha}\cdot\frac{1}{\sin(\theta-\beta)\cos(\theta-\alpha-\delta-\phi)}-\frac{c_wh}{\cos\alpha}\cdot\frac{\sin(\theta-\phi-\alpha)\sin(\theta-\beta)}{\sin(\theta-\beta)\cos(\theta-\alpha-\delta-\phi)} \tag{15}$$

主动土压力应是所有可能滑裂面倾角 $\theta$ 中所对应的土压力 $E$ 的最大值, 相应的滑裂面倾角为 $\theta_{cr}$。可先由 $dE/d\theta=0$, 解出 $\theta_{cr}$, 再代入式(15)得出 $E_a$ 的解析式, 为此:

令

$$b_1=\frac{1}{2}\gamma h^2\frac{\cos(\alpha-\beta)}{\cos^2\alpha}+\frac{(q+\gamma z_0)h\cos\beta}{\cos\alpha} \tag{16}$$

$$b_2=\frac{(c'+u_s\tan\phi)h\cos(\alpha-\beta)\cos\phi}{\cos\alpha} \tag{17}$$

$$b_3=\frac{c_wh}{\cos\alpha} \tag{18}$$

则:

$$E=b_1\cdot\frac{\cos(\theta-\alpha)\sin(\theta-\phi)}{\sin(\theta-\beta)\cos(\theta-\alpha-\delta-\phi)}-b_2\cdot\frac{1}{\sin(\theta-\beta)\cos(\theta-\alpha-\delta-\phi)}-b_3\cdot\frac{\sin(\theta-\phi-\alpha)\sin(\theta-\beta)}{\sin(\theta-\beta)\cos(\theta-\alpha-\delta-\phi)} \tag{19}$$

对式(19)进行三角变换并化简得:

$$E=\frac{b_1[\sin(2\theta-\phi-\alpha)+\sin(\alpha-\phi)]-2b_2-b_3[\cos(\beta-\phi-\alpha)-\cos(2\theta-\phi-\alpha-\beta)]}{\sin(2\theta-\phi-\delta-\alpha-\beta)+\sin(\alpha+\phi+\delta-\beta)} \tag{20}$$

令: $\chi=2\theta-\phi-\delta-\alpha-\beta$

$$\text{则: }E=\frac{b_1[\sin(\chi+\delta+\beta)+\sin(\alpha-\phi)]-2b_2-b_3[\cos(\beta-\phi-\alpha)-\cos(\chi+\delta)]}{\sin\chi+\sin(\alpha+\delta+\phi-\beta)} \tag{21}$$

令 $\frac{dE}{d\theta}=0$ 得:

$$[-b_1\sin(\delta+\beta)-b_3\cos\delta]+[b_1\cos(\delta+\beta)\cdot\sin(\alpha+\delta+\phi-\beta)-b_1\sin(\alpha-\phi)+2b_2-b_3\sin\delta\cdot\sin(\alpha+\delta+\phi-\beta)+b_3\cos(\beta-\phi-\alpha)]\cos\chi+[-b_1\sin(\delta+\beta)\sin(\alpha+\delta+\phi-\beta)-b_3\cos\delta\cdot\sin(\alpha+\delta+\phi-\beta)]\sin\chi=0 \tag{22}$$

在式(22)中, 令:

$$d_1=[-b_1\sin(\delta+\beta)-b_3\cos\delta] \tag{23}$$

$$d_2=[b_1\cos(\delta+\beta)\sin(\alpha+\delta+\phi-\beta)-b_1\sin(\alpha-\phi)+2b_2-b_3\sin\delta\cdot\sin(\alpha+\delta+\phi-\beta)+b_3\cos(\beta-\phi-\alpha)] \tag{24}$$

$$d_3=[-b_1\sin(\delta+\beta)\sin(\alpha+\delta+\phi-\beta)-b_3\cos\delta\sin(\alpha+\delta+\phi-\beta)] \tag{25}$$

则有:

$$d_1+d_2\cos\chi+d_3\sin\chi=0 \tag{26}$$

经三角变换得:

$$(d_1-d_2)\tan^2\frac{x}{2}+2d_3\tan\frac{x}{2}+(d_1+d_2)=0 \quad (27)$$

解(27)式得:

$$\tan\frac{x}{2}=\frac{-d_3-\sqrt{d_3^2+d_2^2-d_1^2}}{d_1-d_2} \quad (28)$$

则:

$$\theta_{cr}=\arctan\left(\frac{-d_3-\sqrt{d_3^2+d_2^2-d_1^2}}{d_1-d_2}\right)+\frac{\phi}{2}+\frac{\delta}{2}+\frac{\alpha}{2}+\frac{\beta}{2} \quad (29)$$

将式(29)所得的滑裂面倾角 $\theta_{cr}$ 带入(15)式可得主动土压力 $E_a$。

## 2 算例分析

某挡土墙,墙高 $H=8$ m、作用在填土表面的超载 $q=10$ kN/m,填土重度 $\gamma=18.6$ kN/m$^3$,有效应力指标 $c'=10$ kPa,$\phi=25°$,填土的平均吸力摩擦角 $\varphi=15°$,$m=3.774$,$n=6.063$,其他有关参数及计算结果列于表 1。

表 1 主动土压力算例

Tab. 1 Example for calculation of active earth pressure

| α (°) | β (°) | δ (°) | $c_w$ / kPa | ω (%) | $E_a$/(kN·m$^{-1}$) 朗肯公式 | 文献[13] | 本文公式 |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 15 | 92.30 | 92.30 | 92.30 |
| 0 | 0 | 0 | 0 | 20 | 145.40 | 145.40 | 145.40 |
| 0 | 0 | 0 | 0 | 25 | 163.06 | 163.06 | 163.06 |
| 0 | 0 | 0 | 0 | 30 | 169.97 | 169.97 | 169.97 |
| 0 | 0 | 0 | 0 | 35 | 173.10 | 173.10 | 173.10 |
| 5 | 10 | 10 | 10 | 15 | — | 99.75 | 99.75 |
| 5 | 10 | 10 | 10 | 20 | — | 153.93 | 153.93 |
| 5 | 10 | 10 | 10 | 25 | — | 172.10 | 172.10 |
| 5 | 10 | 10 | 10 | 30 | — | 179.24 | 179.24 |
| 5 | 10 | 10 | 10 | 35 | — | 182.48 | 182.48 |

注:取 $\gamma=18.6$ kN/m$^3$,$H=8$ m,$q=10$ kN/m,$m=3.774$,$n=6.063$,$c'=10$ kPa,$\phi=25°$,$\varphi=15°$,—表示不适用。

由表 1 知,随着土的含水量增加,主动土压力增大。当含水量小于 25% 时,土压力从含水量为 15% 时的 92.30 kN/m、99.75 kN/m 增大到含水量为 25% 时的 163.06 kN/m、172.10 kN/m,土压力随含水量的变化明显,变化幅度较大;当含水量大于 25% 时,土压力的变化幅度明显减小;若不考虑吸力的影响,即膨胀土饱和时的土压力分别为 177.10 kN/m、186.64 kN/m,结果偏于保守。对符合朗肯假设条件的情况,本文公式与朗肯公式计算结果完全相同与文献[13]库仑精确解的计算结果一致。

## 3 结论

本文基于库仑土压力的基本原理,考虑非饱和膨胀土的含水量与强度之间的关系及墙背粘着力等相关因素,运用数学与力学方法,推得了非饱和膨胀土主动土压力计算的解析式,利用该解析式可直接得出膨胀土的主动土压力及填土滑裂面与水平面的夹角。算例分析表明,随着含水量的增加,主动土压力增大,而变化幅度逐渐减小;实际算例检验表明了本文公式的合理性;公式计算简便、精度可靠,具有一定的工程应用价值。

参考文献(References):


[1] 王年香,章为民,顾行文,曾友金. 膨胀土挡墙侧向膨胀压力研究[J]. 水利学报, 2008, 39(5): 580-587. (WANG Nian-xiang, ZHANG Wei-min, GU Xing-wen, ZENG You-jin. Lateral swelling pressure of expansive soil acting on retaining wall due to inundation[J]. SHUILI XUEBAO, 2008, 39(5),: 580-587. (in Chinese))

[2] 吴珺华,袁俊平,卢廷浩. 非饱和膨胀土边坡的稳定性分析[J]. 岩土力学, 2008, 29(Supp.) 364-367. (WU Jun-hua, YUAN Jun-ping, LU Ting-hao. Stability analysis of unsaturated expansive soil slope[J]. Rock and Soil Mechanics, 2008, 29(Supp.) 364-367. (in Chinese))

[3] 姚攀峰,张明,戴荣,等. 非饱和土的广义朗肯土压力[J]. 工程地质学报, 2004, 12(3): 285-291. (YAO Pan-feng, ZHANG Ming, DAI Rong, et al. GenericRankine theory for unsaturated soils[J]. Journal ofEngineering Geology, 2004, 12(3): 285-291. (in Chinese))

[4] 张常光,张庆贺,赵均海. 非饱和土抗剪强度及土压力统一解[J]. 岩土力学, 2010, 31(6): 1871-1876. (ZHANG Chang-guang, ZHANG Qing-he, ZHAO Jun-hai. Unified solutions of shear strength and earth pressure forunsaturated soils[J]. Rock and Soil Mechanics, 2010, 31(6): 1871-1876. (in Chinese))

[5] Pufahl D E, Fredlund D G, Rahardjo H. Lateral earth pressures in expansive clay soils[J]. Canadian Geotechnical Journal, 1983, 20(2): 228-241.

[6] 尚军. 考虑非饱和土强度理论的土压力问题研究[J]. 岩土工程界, 2007, 10(7): 27-29. (SHANG Jun. Research of earth pressure problems considering unsaturated soil strength theory[J]. Geotechnical Engineering World, 2007, 10(7): 27-29. (in Chinese))

[7] 王晓亮,李光范,杜娟,等. 降雨和蒸发对非饱和土土压力的影响[J]. 应用力学学报, 2014, 31(3): 423-427. (WANG Xiao-liang, LI Guang-fan, DU Juan, et al. Influence of rainfall and evaporation on soil pressure of unsaturated soil[J]. Chinese Journal of Applied Mechanics, 2014, 31(3): 423-427. (in Chinese))


(下转第 156 页)

度的确定[J]. 隧道建设, 2007, 27(3): 13-16. (GAN Kun-rong, YANG Yi, LI Jiang-she. Analysis on karst water inflow mechanisms and determination of thickness of safe rock walls: case study on a tunnel[J]. Tunnel Construction, 2007, 27(3): 13-16. (in Chinese))

[10] Pesendorfer M, Loew S. Subsurface Exploration and transient pressure testing form a deep tunnel in fractured and karstified limestones(Lotschberg Base Tunnel, Switzerland)[J]. International Journal of Rock Mechanics and Mining Science, 2009, 47(1): 121-127.

[11] 李利平, 李术才, 张庆松. 岩溶地区隧道裂隙水突出力学机制研究[J]. 岩土力学, 2010, 31(2): 523-528. (LI Li-ping, LI Shu-cai, ZHANG Qing-song. Study of mechanism of water inrush induced by hydraulic fracturing in karst tunnels[J]. Rock and Soil Mechanics, 2010, 31(2): 523-528. (in Chinese))

[12] 李利平, 李术才, 崔金生. 岩溶突水治理浆材的试验研究[J]. 岩土力学, 2009, 30(12): 3642-3648. (LI Li-ping, LI Shu-cai, CUI Jin-sheng. Experimental research on chemical grout for treating water inrush in rock mass[J]. Rock and Soil Mechanics, 2009, 30(12): 3642-3648. (in Chinese))

[13] 张民庆, 刘招伟. 圆梁山隧道岩溶突水特征分析[J]. 岩土工程学报, 2005, 27(4): 421-426. (ZHANG Min-qing, LIU Zhao-wei. The analysis of the features of karst water burst of the Yuanliangshan tunnel[J]. Chinese Journal of Geotechnical Engineering, 2005, 27(4): 421-426. (in Chinese))

[14] 赵明阶, 徐容, 许锡宾. 岩溶区全断面开挖隧道围岩变形特性模拟[J]. 同济大学学报: 自然科学版, 2004, 06: 710-715. (ZHAO Ming-jie, XU Rong, XU Xi-bin. Deformation modeling of surrounding rock during full-face excavation of tunnel in karst regions[J]. Journal of Tongji University: National Science, 2004, 32(6): 710-715. (in Chinese))

[15] 赵明阶, 刘绪华. 隧道顶部岩溶对围岩稳定性影响的数值分析[J]. 岩土力学, 2003, 24(3): 445-449. (ZHAO Ming-jie, LIU Xu-hua. Numerical analysis of influence of karst caves in top of tunnel on stability of surrounding rock masses[J]. Rock and Soil Mechanics, 2003, 24(3): 445-449. (in Chinese))

[16] 王勇, 乔春生, 孙彩虹等. 基于 SVM 的溶洞顶板安全厚度智能预测模型[J]. 岩土力学, 2006, 27(6): 1000-1004. (WANG Yong, QIAO Chun-sheng, SUN Cai-hong. Forecasting model of safe thickness for roof of karst cave tunnel based on support vector machines[J]. Rock and Soil Mechanics, 2006, 27(6): 1000-1004. (in Chinese))

[17] 王琪. 近接溶腔对隧道围岩稳定性影响及防治措施研究[D]. 西安: 长安大学, 2014. (WANG Qi. The study on stability and control measures of tunnel surrounding rock by the nearby karst cave[D]. Xi′an: chang′an university, 2014. (in Chinese))

(上接第 149 页)

[8] 陈铁林, 陈生水, 章为民, 等. 折减吸力在非饱和土土压力和膨胀量计算中的应用[J]. 岩石力学与工程学报, 2008, 27(S2): 3341-3348. (CHEN Tie-lin, CHEN Sheng-shui, ZHANG Wei-min, et al. Application of reduced suction to earth pressure calculation of unsaturated soils and swell increment[J]. Chinese Journal of Rock Mechanics and Engineering, 2008, 27(S2): 3341-3348. (in Chinese))

[9] 姚攀峰, 张明, 张振刚, 等. 非饱和土土力学工程应用方法[J]. 工程地质学报, 2005, 13(3): 346-352. (YAO Pan-feng, ZHANG Ming, ZHANG Zheng-ang, QI Shen-gwen. Mplementation method of the unsaturated soil mechanics in engineering[J]. Journal of Engineering Geology, 2005, 13(3): 346-352. (in Chinese))

[10] 姚攀峰, 张明, 刘晓春, 等. 北京地区非饱和土土压力初步研究[J]. 建筑结构, 2005, 35(5): 57-59. (YAO Pan-feng, ZHANG Ming, LIU Xiao-chun, et al. Research on unsaturated soils earth pressure in Beijing[J]. Building structure, 2005, 35(5): 57-59. (in Chinese))

[11] 赵均海, 梁文彪, 张常光, 等. 非饱和土库仑主动土压力统一解[J]. 岩土力学, 2013, 34(3): 609-614. (ZHAO Jun-hai, LIANG Wen-biao, ZHANG Chang-guang, et al. Unified solution of Coulomb′s active earth pressure for unsaturated soils.[J]. Rock and Soil Mechanics, 2013, 34(3): 609-614. (in Chinese))

[12] 朱志铎, 刘松玉. 非饱和膨胀土的主动土压力分析[J]. 公路交通科技, 2001, 18(5): 8-10. (ZHU Zhi-duo, LIU Song-yu. Analysis of active earth pressure of unsaturated expansive soil[J]. Journal of Highway and Transportation, 2001, 18(5): 8-10. (in Chinese))

[13] 胡晓军. 基于库仑理论的非饱和膨胀土主动土压力计算[J]. 路基工程, 2006(4): 73-76. (HU xiao-jun. Active earth pressure calculation of unsaturated expansive soil based on Coulomb theory[J]. Subgrade engineering, 2006(4): 73-76. (in Chinese))

[14] 韩华强, 陈生水, 郑澄锋. 非饱和膨胀土强度及变形特性试验研究[J]. 岩土工程学报, 2008, 30(12): 1872-1876. (HAN Hua-qiang, CHEN Sheng-shui, ZHENG Cheng-feng. Experimental study on strength and deformation of unsaturated expansive soils[J]. Chinese Journal of Geotechnical Engineering, 2008, 30(12): 1872-1876. (in Chinese))

[15] 徐永福, 刘松玉. 非饱和土强度理论及其工程应用[M]. 南京: 东南大学出版社, 1999: 11. (XU Yong-fu, LIU Song-yu. Strength theory of unsaturated soils and its engineering application[M]. Nanjing: Southeast University Press, 1999: 11. (in Chinese))