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Numerical simulation and verification of the loose dumping limiting height

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Abstract. Common deformation and intensity control theory systems for determining the waste dump limiting height ignore the influence of topsoil basal thickness. The research of Yan Rong-gui et al indicates that the interaction mechanism between flat base site and loose dumping is crucial to determine the waste dump limiting height. But there is hardly any correlation analysis of the numerical simulation. Connecting with project examples, firstly using the theoretical formula to determine the limiting height-(61-97) m. When considering the topsoil basal thickness, the value can be raised to 280m safely. Then establish the numerical model of thin topsoil basement case and thick overburden basement case for finite element simulation and verification, the results show that the effect of dump load mainly acts on the bedrock with the thin topsoil basement mainly transferring the load. The thick overburden basement bears the weight of the dump in the second case, and certainly the dump limiting height determines by the deformation and intensity control theory systems. Based on the strength reduction finite element method, we get safety factor consistent with the limit equilibrium analysis. The results of numerical simulation analysis not only verify the interaction mechanism between flat base site and loose dumping but further improve the algorithm for determination of waste dump limiting height, what's more, provides more scientific basis for extended using of this kind of idea, method and formula for determining waste dump limiting height. From another point of view, it also provides meaningful reference for mine disaster prevention and mitigation.

Keywords. Numerical analysis, the intensity control, the waste dump limiting height, critical thickness, super-high bench dumping-site, foundation loading.

1. Introduction

Dump construction is an important part of mine construction in China. It is playing a more and more important role in saving mine cost and reducing the area of mine land. Many mines are trying to raise dump height and build super large dump with a volume of several hundred million m^3 in order to achieve greater efficiency (Dumps such as the Dagushan Railway Dump, Gongchangling vehicle dump and railway dumps, Zhujiabaobao iron ore dump have a single dump site volume of more than 100 million cubic meters). European countries and the United States stipulate regulations on the dumping slope and height to ensure the stability of the dump site and reach the goal of environmental protection and reclaiming soil. In contrast, the mines in China pay more attention to economic factors, pursuing less land with huge capacity in the design of the dump, therefore height is the most important factor in the construction of super large dump. The main technical bottlenecks facing the dumping height determination is: the waste dump limiting height determined by the common basement carrying capacity or the deformation control limiting height calculation system can't satisfy the need of an ultra-high-level dump [1]. In previous research designs, the researchers neglected the impact of the topsoil thickness on the dump height, which would resulting in very conservative conclusions and influence the economic benefits of the mine. Yan Ronggui, He Yueguang et al. started from the topsoil basement thickness and barren rock contact condition to discuss the gentle topsoil basement mechanism under the influence of dumping load effect. They derived the calculation methods and formula of critical topsoil thickness and the dump limiting height, and put them into practice. According to their calculation, the limit height of Qijiagou dump under deformation control is 75.7 ~ 93.5m, the limit height in terms of bearing capacity is 42 ~ 96.1m without considering the basement topsoil thickness. When considering the thickness of the topsoil, the loading mechanism of the dump basement will be changed. Now, the height of the dump in Qijiagou has increased to 400m, and the raise rate is as high as 300%. The dump is in stable operation and producing significant economic benefits [2]. The research results have improved and developed a general algorithm to determine the dump height; it also laid a theoretical basis for improving the thick soil surface and improving the stability of the dump. However, there are few numerical simulation analysis and verification of the mechanism up to now. Based on the numerical simulation and analysis of the basement carrying capacity and limiting height of the dumping site of No.2 mine of Nanfen Iron Mine, the geotechnical mechanics between the accumulation body and the topsoil of the basement is studied so as to provide a clearer theoretical basis for the construction of the dump.

2. A General Calculation System for Limit Dump Height [3-6]

At present, the determination of dump height of gentle basement at home and abroad mostly depends on the bearing capacity of subsoil substrate or the deformation characteristics of topsoil substrate.

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2.1. Deformation control

Assuming the basic parameters of the dump are: Dump hight H, bulk solid density γ, the dead weight of the bulk γH. Under the impact of γH, the compressive deformation of underlying subsoil is:

$$\Delta h = \gamma H \cdot \alpha h/(1 + e_1) \quad (1)$$

Where α is the compression coefficient of base soil, e_1 is the void ratio, h is the thickness of the underlying subsoil.

Considering the impact of instability on dump operation safety and surrounding environment (human, equipment and construction), the following deformation of the basement $\Delta h/h = (15{\sim}20)\%$ is taken as the standard of the limiting height.

2.2. Intensity control of limiting height

According to the loose media statics theory [7] of Sarkalovsky, when the base is horizontal, the external load perpendicular to the ground, the function between maximum pressure and the foundation soil in a state of limit equilibrium is as follows:

$$P + H' = (C + H')\, tan^2(\frac{\pi}{4} + \frac{\phi}{2})e^{0.5\pi\, tan\, \phi} \quad (2)$$

Where P is the ultimate bearing capacity (maximum pressure); $H\,'$ is the load factor, $H' = qc\, tan\, \phi$; C is the soil cohesion; ϕ is the internal friction angle; q is the basement load.

According to "Code for Design of Non-ferrous Metal Mine Dump" (GB 50421-2007), with reference to "Mining Manual" and L.Prandtl load-bearing formula, when the basement is in the limit state, losing bearing capacity and producing plastic deformation and movement, with the unified use of international single ($1MPa = 10.2kg/cm^2 = 10.2 \times 10^4 kg/m^2$) [7] , the limiting height is:

$$H_2 = c \times cot\, \phi\, \gamma^{-1}[tan^2(\frac{\pi}{4} + \frac{\phi}{2})e^{\pi tan_\phi} - 1 \quad (3)$$

It is not difficult to find that the limit height H of the soil field is independent of the absolute thickness of the underlying subsoil, which means, the determination of the limit height H does not reflect the effect of the thickness h of the underlying subsoil.

3. Load - bearing mechanism of dump site considering the impact of thickness

Dump is far different from the general structure; it is a rock mass composed by different shapes and different sizes of loose stone. Dump gravity load acts on the topsoil through its bottom surface, the discrete stones in the bottom acts on the lower base topsoil with different stress concentration factor. This contact state determines that the topsoil has been controlled by stress concentration during the formation of the subsoil. Under the low bearing capacity, the topsoil of the basement is subjected to shear failure. The macroscopic appearance is that the topsoil is squeezed into the fragment of gravel. The initial height depends on the size of the gravel, and the volume squeezed in is determined by the porosity of the gravel. This shear failure is not equivalent to the instability of the dump. After the formation of the bottom continuous mixture layer, the upper load acts on the topsoil or bedrock beneath the mixed layer. If the topsoil has sufficient thickness and the cohesion of the soil is insufficient to prevent the formation of floor heave under the impact of load effect, it will result in dump instability.

Therefore, for the flat basement dump, considering the thickness of the topsoil and the contact conditions between the topsoil and the bottom waste rock, the impact of the topsoil on the stability of the dumping site can be divided into the following three situations:

1) Very thin topsoil base ($h < h_0$). When the topsoil thickness h is not enough to fill the stone gap at the bottom of dump, or known as less than the thickness h_0 soil layer squeezed into the waste rock at the bottom of the dump, i.e., it is called very thin topsoil base when $h < h_0$.When $h = h_0$, it is called the critical thin topsoil base.

The critical topsoil thickness h_0 can be determined by the statistical mathematical method using the waste rock and the topsoil property at the bottom of the dumping site after the punching shear. If the average grain diameter of stone at the bottom of the dump is d_m, void ratio is e_1, stone is arranged by random media particle, engineering error is 1%, numbers of topsoil stone layer is m, h0 can be e by the following formula:

$$h_{0min} = \sum_{i=1}^{m} d_m \left(\frac{e_1}{1+e_1}\right)^m \quad (4)$$

$$h_{0max} = m d_m \left(\frac{e_1}{1+e_1}\right) \quad (5)$$

Then$h_{0min} < h_0 < h_{0max}$

2) Thin topsoil base ($h_0 < h < h_1 + h_0$). When the thickness h of the topsoil is greater than the critical thickness h_0, there will be excess topsoil remaining in the lower part of the waste rock and soil mixture at the bottom of the dumping site. On the one hand, the superficial topsoil forms an outer drum in the outer edge of the slope toe under the influence of shearing stress; on the other hand, the topsoil cohesion prevents it from forming the outer drum. When the two are balanced, i.e. the critical thickness of the topsoil floor heave reaches h1, based on L.Prandtl foundation bearing capacity and according to loose media Mechanics theory of Sakalovsky, the critical thickness of the topsoil floor heave h1 can be determined by the following formula:

$$h_1 = 2C \cdot ctg\beta/ \quad (6)$$

Where C is the topsoil cohesion; β is the overall slope angle of the dump; γ is the bulk weight of the dump.

3) Thick topsoil base ($h > h_1 + h_0$). When the topsoil thickness$h > h_1 + h_0$, the dump height can be calculated by the calculation formula of limiting height under deformation control or strength control. When the limit state is reached, the topsoil of the basement is in total shear failure, and the topsoil slips out from the floor heave of the dump slope. The maximum shear stress in the topsoil is located below the midpoint of the slope, and the shear failure and the floor heave lead to uneven settlement and the instability of the slop.

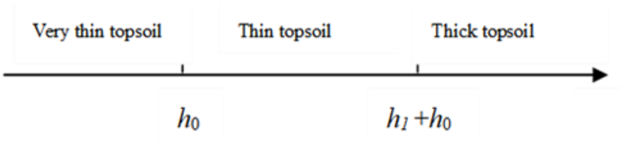

Figure 1. Classification of waste dump topsoil base

Based on the above analysis, it can be concluded that in the case of very thin topsoil and thin topsoil, the topsoil is only subjected to punching and shearing failure. It is characterized by that the unapparent failure surface profile, the significant vertical compression of the soil under the waste rock, the small topsoil perturbation on both sides. In this case, the dump height can be calculated by the bearing capacity of underlying bedrock. In the case of thick topsoil base, when the thickness of the underlying soil exceeds the critical thickness and the underlying soils are in the form of bottom drum, the soil heap pile height can be calculated by general deformation control or intensity control system.

4. Numerical Simulation of Example Project

4.1. Site Overview

The No. Ⅱ dumping site of Nanfen open-pit iron ore mining area is composed of the original No. 2 and No. 3 dumping sites. It is located on the upper part of the stope, consisting three rock dumping areas, from north to south are Nanfen Dadonggou, Fengjia Donggou and Huangbaiyu river north side valley (Yong'an Village), and numbered No. 1, 2, 3 area respectively. The rock dumping volume designed for No. Ⅱ dumping site is 450 million tons, the heap volume is 205 million m^3, and the dumping height is 200m ~ 300m. Area No.1 and No. 2 are dominated by the single-stage, high-banding soil, the stage height reaches 280m, the annual advance speed of the soil line is about 6 ~ 10m, in the design, the final stage height will reach 320m, the elevation of slope top and slop foot are 600m, 320m ~ 330m respectively, and the current slope toe is 33^o ~ 35^o.

Taking the area No. 2 as the research object, the dump site is a “U” type valley, the gradient of the east-west main channel is slow (3%), and the inclination of the north and south sides is 13-25 degrees. The barren rocks are mainly from the upper plate rock, mostly are the granite, chlorite, quartz feldspar schist, phyllite, hornblende schist. The underlying Quaternary basal topsoil has a thickness of 1-3m, with the bedrock mostly composed of undeveloped pale blue marlstone of the Nanfen Formation from sinian system, the integrity is good, which won’t cause stability problem. Now the largest profile of the slope is selected to establish the numerical model shown in Figure 2, where the elevation of slope toe is 320m, the elevation of slope top is 600m, the upper row of waste dumping material are filled with tape material, topsoil is composed by gravel soil and subterrane. the underlying bedrock is slightly weathered and the lithology is pale blue marl σc = 31.21MPa, E = 6.5e4MPa. The bulk weight of tape material γ= 2.10 t/m3, overall slope toe is 35.8^o. Due to the technical constraints, the maximum allowable particle size of the tape rock discharging system is 350mm, and the on-site screening results show that d> 200mm (m) only accounts for 5.50%, the actual maximum particle size of 350mm cannot constitute a skeleton, but dissociate in an individual form in the lower level of waste stone matrix, the equivalent maximum particle size d_m = 280mm, which is a balance result to ensure the project security, The porosity ratio e_1= 0.52. The physical and mechanical parameters of the bedrock marlstone are results from the statistical analysis of existing data, combined with supplemented partial shear and triaxial tests for verification and comprehensive selection, as shown in Table 1 below.

Table 1. Physical and mechanical parameters

Lithology	Elasticity modulus /Mpa	Poisoon's ratio	Density /kg.m-3	Cohension /Kpa	Internal friction anlge /o
Belt conveyor dumping	27	0.35	2100	22	31
Gravelly soil	7.1	0.41	1800	21	30
Egg white malm	65000	0.21	2580	490	27.8

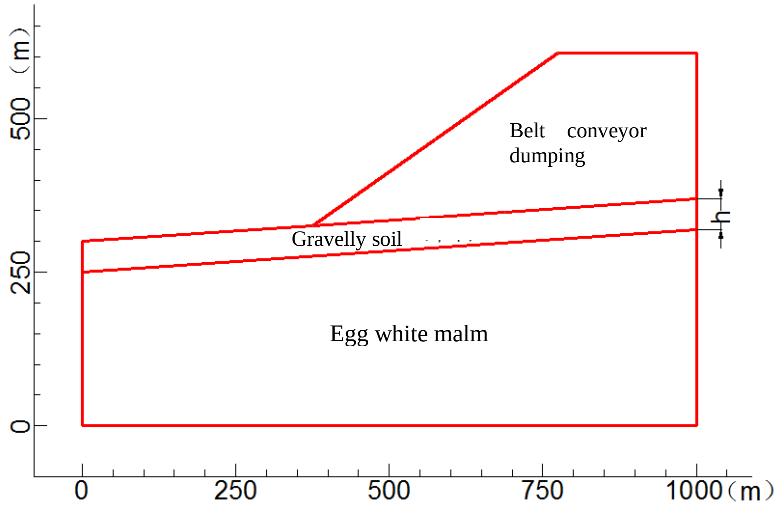

Figure 2. Material line for the waste dump

4.2. Deformation control and intensity control calculation system without considering the thickness of topsoil

4.2.1. Limit height under deformation control

As mentioned earlier, under the gravity load effect, the control conditions of compression deformation of the underlying soil are as follows:

$$H \leq \frac{1+e_1}{\alpha \cdot \gamma}[15\%;20\%] = [15\%;20\%]\frac{Es}{\gamma} = [73.33;97.78]m$$

4.2.2. Limit height under intensity control

As mentioned above, in natural state and under the influence of gravity load effect, the load on the contact surface of basement is not uniformly distributed, rather, it is linearly distributed with the slope toe as 0 and the shoulder as γH , and then the equivalent force on the contact surface is$\gamma H/2$. The control condition of subsoil intensity is:

$$\gamma H/2 = c \cdot \cot\varphi[\tan^2(45+\frac{\varphi}{2})e^{\pi\tan\varphi}-1] \tag{7}$$

Insert$c = 21KPa,\ \phi = 30^o$ into the above formula,

$$H = \frac{2c \cdot \cot\varphi[\tan^2(45+\frac{\varphi}{2})e^{\pi\tan\varphi}-1]}{\gamma} = 61.43\,m$$

The calculation results of deformation control and intensity control analysis are consistent. With the change of topsoil properties, soil height is 61 ~ 97m, which means that the topsoil will be damaged if height is more than 97m. However, the current dump has reached a height of 280m, some places even reach 283m, it still remains overall stability except for the local damage caused by rainfall.

4.3. Influence of topsoil thickness on limit height

4.3.1. Determine the type of topsoil

Take e_1=0.54 as hierarchical control condition, according to $(\frac{e_1}{1+e_1})^{m+1} < 1\%$, it can be obtained that m=4, then:

$$h_{0\min} = \sum_{i=1}^{m} d_m \left(\frac{e_1}{1+e_1}\right)^m = 151 \text{ mm}$$

$$h_{0\max} = md_m \left(\frac{e_1}{1+e_1}\right) = 394\ mm$$

In natural state, the critical thickness h_1 of floor heave required for overall shear failure is:

$$h_1 = 2C \cdot \text{ctg}\beta / \gamma = (2.86 \sim 3.32)\ m$$

Hence, $h = h_0 + h_1 = (3.01\sim3.71)$m

According to the geological survey, the thickness of topsoil is 1.0 ~ 3.0 m in the study area, and the distribution is uneven, the local thickness of the gully reaches 3m, and that of other areas are less than 3m. The foundation of this dump belongs to the thin topsoil. The condition of the failure is not sufficient, and the pile height is determined by the following bedrock. As the uniaxial compressive strength of the underlying bedrock$\sigma_c = 31.21MPa$, the dump load in the thickness of 280m is 5.83MPa, it is obvious that 5.83 / 2 << 31.21 / 3, so the dump is in overall stability.

4.3.2. Numerical simulation of dump height [8-11]

The numerical model is established for elastic-plastic finite element analysis as shown in Figure 2. This Mohr-Coulomb model can be divided into 22642 elements with 22963 nodes. The analysis process has two steps: the GEOSTATIC analysis and Step-2, the former one analyzes the in-situ stress equilibrium in the case of the self-gravity stress field, the later one starts with the stacking calculation of the upper dump. In the process of simulation, the displacements of the points P487 (693.6353, 356.2857) and P549 (414.508, 328.863) on the interface between the dump and the basement were measured. First, the displacement pattern of the 280m high dump was simulated at h = 1 ~ 3m, then the displacement model of the dump in the case of a 50m topsoil was set up to verify the effect of the topsoil thickness on the limiting height of the dump.

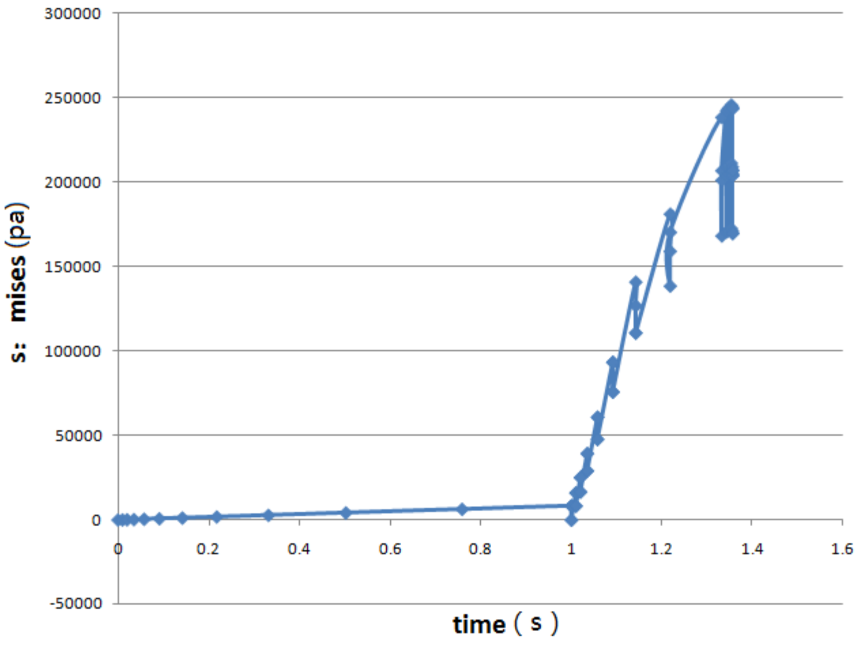

Figure 3. S: Mises and time curve

In the actual situation, h = 1 ~ 3m, if taking the value of 3m, the change curve of the stress in test point P549 can be found in Figure3. It can be seen from Figure3 that the internal force tends to be stable in the calculation of the ground stress equilibrium. With the loading of upper part of the dump, the bottom of the soil layer shows a honeycomb contact in places where there is higher stress concentration than the average stress value of the stress concentration, macroscopically expressed as punching shear caused by soil erosion. According to what mentioned above, the theoretical calculation of the extrusion volume is [149; 392] mm, which can be show by the Displacement and time curve of the point P549 in Figure 4. When the metalling punched by shear damage squeezing into the loose accumulation for 0.369 m, it will no longer squeeze in. The thickness of the soil below the surface is 2.63m, which does not reach the critical thickness. The dumping site is mixed with the sub layer topsoil to show an overall impact on the bedrock.

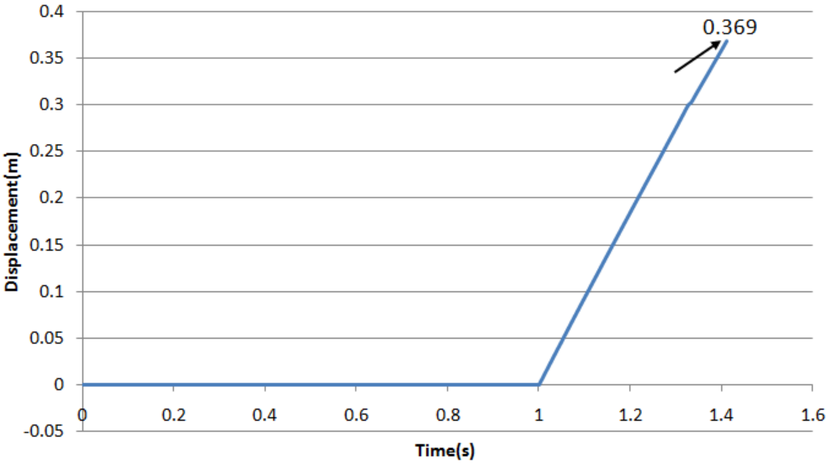

Figure 4. Displacement and time curve of the point P549

The displacement nephogram under present situation obtained by finite element analysis is shown in Figure 5. The relationship curve of Fs along with the change of U1 is shown in Figure6. If the displacement inflection point is taken as the evaluation criterion, the safety factor F_s = 1.06, which is consistent with the Fs = 1.005 obtained from limit equilibrium analysis, therefore it is proved that the slope is stable.

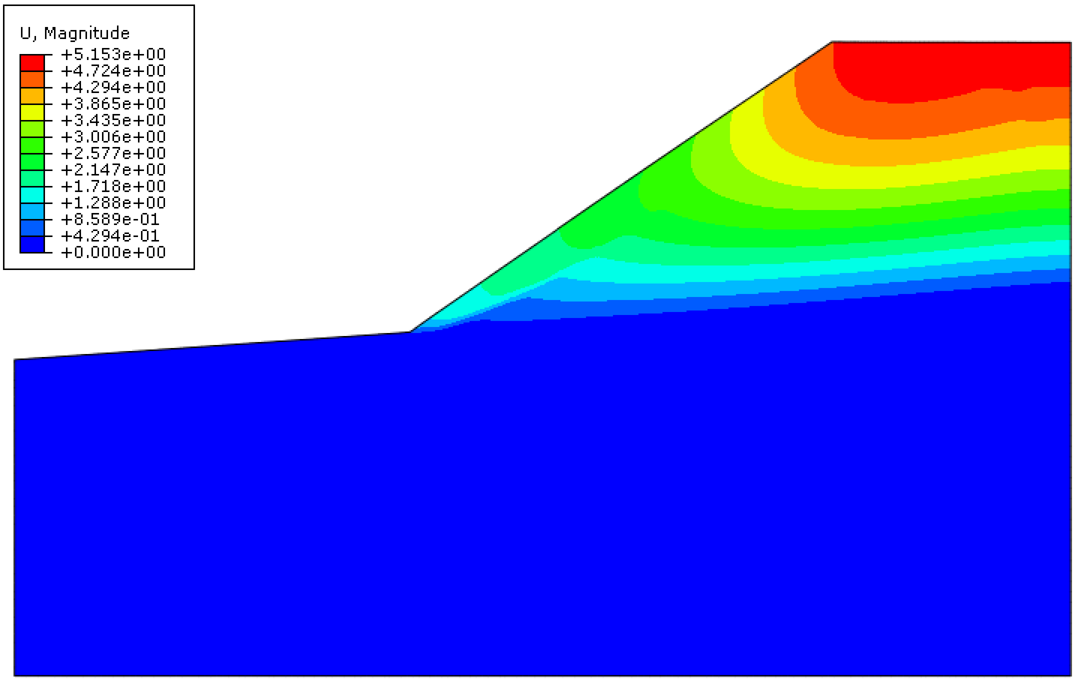

Figure 5. Displacement nephogram under present situation

When the topsoil layer h = 50m, the displacement and time curve of the point P487 in the U2 direction is shown in Figure7. The trend of slope instability is reflected in the incremental displacement, in the case of t=0.9396s and t=0.8868s, the incremental displacement changes significantly, as shown in Figure 8. It can be seen that the gravel layer with shear failure is no longer squeezed when the displacement reaches 0.396 m. At this time, the thickness of the lower soil layer is much larger than the critical thickness. Under the load effect of the upper dump, it is in the limit state, so that the whole stability of the dump is destroyed, and the failure surface can be reflected by the incremental displacement.

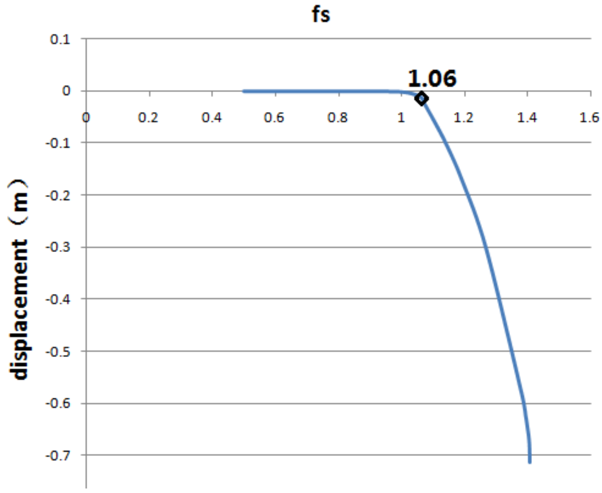

Figure 6. Relationship curve of *F*s along with the change of U_1

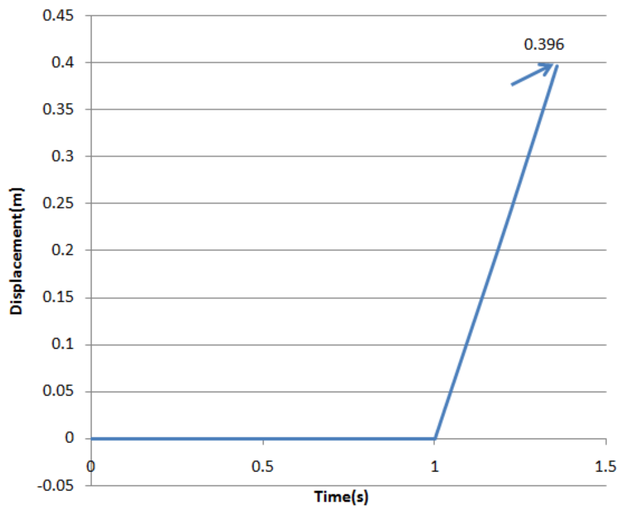

Figure 7. Displacement and time curve of the point P487

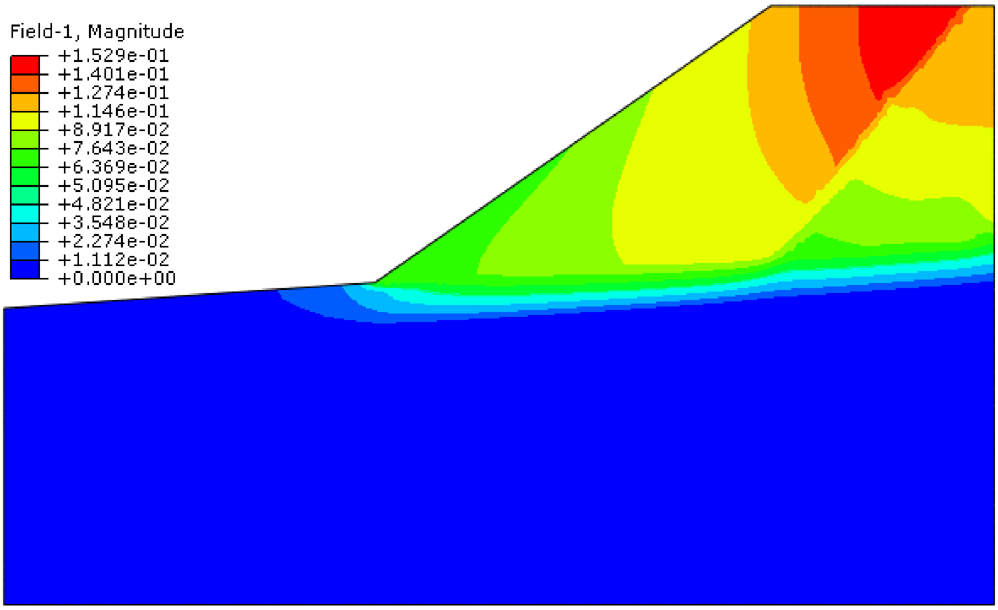

Figure 8. Incremental displacement nephogram

5. Conclusion

(1) Dump with 280m height and topsoil thickness of 3m and 50m thick can be classified into the thin topsoil type and the thick topsoil type respectively, the numerical simulation of which shows that the base topsoil are compressed 0.369m and 0.396m respectively, i.e. the topsoil is squeezed into the dump by 0.396m and 0.396m, which is in agreement with the theoretical results. In the case of thin topsoil, the dumping soil and the lower part of the topsoil mix together to form an integral action on the bedrock. In the case of thick topsoil, the topsoil is squeezed into the dump by a certain thickness, and the thickness of the bottom soil is far beyond the critical thickness. The topsoil of the base undergoes a punching shear failure and is squeezed into the waste rock; the whole shearing damage causes the dumping to roll out from the toe of the slope, resulting in instability of the dump.

(2) During the construction of the dumping site, for dump with flat topsoil, the limiting height of the dump can't be directly determined by the bearing capacity of topsoil without considering the influence of the topsoil thickness. In this paper, a finite element model is established based on an engineering example to verify the effect of topsoil thickness on the limit height, which also verifies the action mechanism between dump body and topsoil, and the numerical analysis results are consistent with theoretical deduction results, providing a scientific basis for the determination of dump height.

(3) After learning the downward transfer mechanism of load in the dump, in the construction planning stage, the topsoil type in the dump field should be determined first. In order to maintain stable operation afterwards, topsoil stripping treatment can be applied to the regions with larger thickness, in order to reduce its thickness into acceptable scope, to a certain extent providing a meaningful reference for the construction of dumping and disaster prevention.

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