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Arch. Min. Sci., Vol. 59 (2014), No 4, p. 959–970

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.2478/amsc-2014-0066

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RESEARCH ON THE INFLUENCE OF EXCAVATION AND LOADING ON Z-DIRECTION DISPLACEMENT IN SURROUNDING SOIL MASS

BADANIA WPŁYWU PRAC WYDOBYWCZYCH I SKŁADOWANIA NA WIELKOŚĆ PRZEMIESZCZENIA GRUNTU W KIERUNKU *Z* W OTACZAJĄCYM GÓROTWORZE

To probe into the pattern in which the excavation and loading process have on such factors as stress and displacement in neighboring regions of deep open pits, a mechanical unloading model in coal mining process and another model for the loading process are set up respectively. Besides, FLAC^{3D} software is used to simulate dynamic excavating and loading process in open pits and record such data as the unbalanced stress, unloading strength and displacement fluctuations, which further serve as basis for studying the functional relationship about different mining heights and scope of influence using fitting method. The research results indicate that the unloading strength enhances with increasing mining depth in a linear fashion. In addition, a noticeable displacement circle takes shape around the stope, which would also extends with growing mining depth. As to waste loading, it brings about large-scale surface subsidence in neighboring regions, which follows a logarithm function convergence pattern with the distance away from the dump border. Under combined effects of excavation and loading, the value of the soil mass displacement would increase with growing mining depth and loading height. Specifically, the soil displacement at a distance of 100 m away from the stope border (around 200 m away from the outer dump border) is abnormally significant and it further develops at a rate of 0.0228 mm/h.

Keywords: excavation, loading, unloading strength, stress, region displacement, displacement circle

W celu zbadania zależności pomiędzy procesami wydobycia i składowania urobku a takimi czynnikami jak naprężenia i przemieszczenia w sąsiadujących partiach głębokich wyrobisk odkrywkowych, wykorzystano model mechaniczny procesu urabiania węgla oraz model procesu jego składowania. Wykorzystano oprogramowanie FLAC 3D do symulacji procesów wydobycia i składowania w wyrobiskach odkrywkowych, zapisano odpowiednie dane: niezrównoważone naprężenia, wytrzymałość w trakcie odciążania oraz wahania przemieszczeń gruntu, które wykorzystane zostały następnie jako podstawa do badania funkcjonalnych zależności pomiędzy wysokością poziomu wydobycia a skalą oddziaływania, przy użyciu

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odpowiednich metod dopasowania. Wyniki badań wskazują, że wytrzymałość w trakcie odciążania wzrasta liniowo z głębokością. Ponadto, zarejestrowano wyraźny kołowy przebieg przemieszczenia wokół zbocza, który także rośnie z głębokością. W przypadku obciążenia wskutek urobku odpadowego, zanotowano obniżenia terenu o dużym zasięgu o przebiegu konwergencji opisanym funkcją logarytmiczną odległości od miejsca składowania urobku odpadowego. W przypadku wystąpienia połączonych efektów wydobycia i składowania, wielkość przemieszczeń mas gruntu wzrastać będzie wraz z głębokością prowadzenia prac i wysokością składowania. Przemieszczenie gruntu w odległości 100 m od brzegu wyrobiska (ok. 200 od zewnętrznej granicy składowiska) okazuje się niepokojąco duże i postępujące w tempie 0.0228 mm/h).

Słowa kluczowe: wydobycie, składowanie, wytrzymałość gruntu w trakcie składowania, naprężenia, przemieszczenia, kołowy przebieg przemieszczenia

1. Introduction

As a common practice in geotechnical engineering, excavation and loading are liable to induce various stress unloading and surface deformation on strata of distinct lithology. A lack of knowledge about relevant patterns would directly impede a precise evaluation conducted on the safety of surrounding ground structures. It is certain that waste stripping and dumping would come along with opencast coal mining practice (Cai et al., 2008; Javad Sattarvand & Christian Niemann-Delius, 2013). Due to growing mining depth and long-term loading effect of unbalanced ground stress, displacement and deformation (Rui et al., 1999) would occur in slope area, which, if accumulated to a certain level, would easily bring about slope collapse. On the other hand, when waste loading height continues to grow, the vertical ground stress enhances in proportion as well, which, once delivered onto the foundation, would result in ground upheaval in surrounding areas and affect the foundation evenness and pose a direct threat to human safety (Malinowska, 2013; Molladavoodi, 2013). In this sense, it is of great significance to study the variation pattern of surrounding region displacement in coal mining and loading process and define the scope of influence of large-scale geotechnical projects and structures (Inmaculada et al., 2013).

For instance, Tang Yanfei and Yang Shifei (2008) simulated the regular pattern in which large-scale loading affects horizontal soil mass displacement by applying finite element software. They analyzed the issue that how different factors would affect horizontal and subsidence displacement and acquired quantitative analysis method which could be applied to study how large-area loading affects the surrounding environment. Also, Liu Yue and Huang Qiangbing (2009) made a centrifugal test to study the loess stope deformation features resulting from coal mining and loading practice. They discovered respective slope displacement laws and destruction features before and after the mining process. Before the process, the slope deformation is featured by vertical one under the effect of self gravity stress, whereas after the process, it is vertically downward deformation in the middle and rear part of the slope but horizontal deformation in the front. In addition, Lin Gang et al. (2010) have studied the characters of retaining structures for deep foundation pit excavation under unbalanced heaped load by numerically simulating the entire process. Their study has revealed the distinction in terms of internal forces and displacement between the retaining structures on both sides of the foundation pit and they have drawn general rules of further referential value. Also, Yang Min et al. (2002) by studying a certain industrial building collapse accident caused by heaped loading claimed that long-term loading or even heaped loading is mainly responsible for substantial lateral displacement in adjacent pile foundation and collapse of factory building roof. They further proposed a set of standards to control heaped loading and pile foundation deformation.

At present, it is commonly acknowledged that excavation and loading process are certain to cause soil mass displacement and the relevant variation pattern has been obtained as well. When it comes to opencast coal mining, the earthwork volume generated in the process is huge and surface displacement is obvious to notice (Huang et al., 2013). Excavation and loading work in coal mining is different from that in construction sites and the difference lies in the fact that stope formed in former situation is like an inverted prismoid with non-vertical walls, which is wide in the upper part and narrow in the lower. Considering that a stable stope is essential for safe mining production, it is of great value and significance to study the relevant pattern which could be in turn used to guide program planning in opencast coal mining and dumping.

2. Mechanical features in excavation and loading process

2.1. Slope unloading features in excavation process

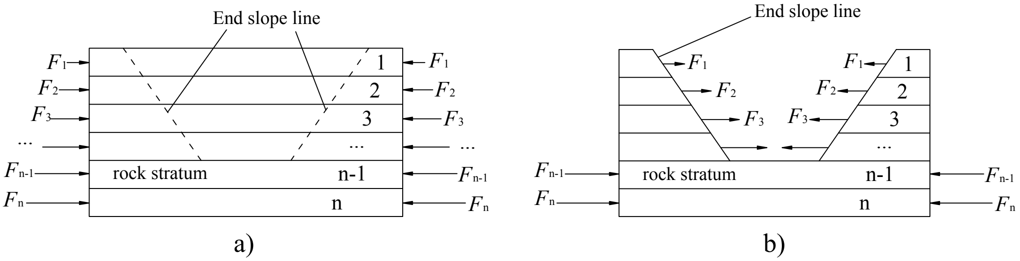
Coal seam occurs horizontally and is therefore mined region by region in deep large-scale open pits. The basic mining procedure goes like it hereunder. Firstly, the overlying soil and rock mass are stripped away to expose coal seams. Following a certain space-time order (Shang et al., 2001), the mining process advances downward all the way to the coal seam floor. Then the coal stope, with its existing scale, is pushed forward all the way to the frontier of the coal filed. In this process, working slope, end slope and non-working slope gradually take shape. Besides, the unloading value of unbalanced ground stress increases in magnitudes and free slope face extends in proportion. Furthermore, under long-term unloading effect, plastic and elastic deformation occurs to the slope rock body and surface breakage develops as well, resulting in an abnormal structure.

According to fundamental theory concerning ground stress, when mining depth increase, F_n (horizontal pressure), the lateral pressure generated by ground stress goes up as well in a linear manner. Here comes the formula:

$$F_n = \mu\gamma H / (1 - \mu) \tag{1}$$

where: F_n (kN) stands for lateral pressure, μ Poisson's ratio, γ (kN/m^3) the bulk density and H (m) the vertical mining depth.

As the stope advances downward, the unloading situation of unbalanced ground stress in stope area is shown in Fig. 1.



a) b)

Fig. 1. Unbalanced stress unloading in excavation process

As clearly indicated in Fig. 1, there exists a positive and linear correlation between the mining height and unbalanced stress in end slope area. However, when viewed from the perspective of 3D structure, the opencast stope resembles an inverted prismoid, which is wide in the upper part and narrow in the bottom. The accumulation of unbalanced stress along the end stope direction is named 3D unloading effect, under which no fair linear pattern shows up in vertical height.

2.2. Mechanical features in loading process

As open pit extends forward and downward, the overlying rock and soil mass stripped away is usually dumped right next to the stope. The waste piles up on in situ surface and gradually becomes an outer dump with tens of hundreds of meters' height. Long-term loading of such grand geotechnical structure would, in addition to its own subsidence to some extent, exert an influence on the base compactness and evenness. For instance, based on the filed investigation in an open pit in Inner Mongolia Province, various surface bulging takes place surrounding large-scale external dumps after several years. To solve this problem, a number of experts and scholars have been devoted to excavation and loading study by setting up mechanical model (Zhang, 2011) in the process. Fig. 2 is the force structure.

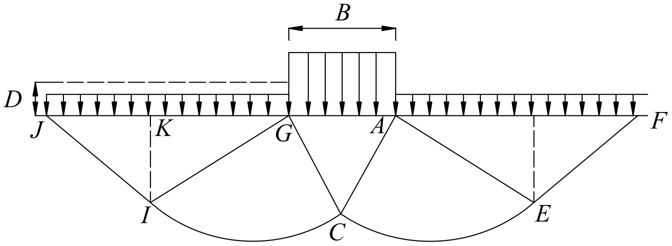


Fig. 2. Force analysis in loading process

In Fig. 2, ΔACG is compaction wedge, *AE* and *GI* are slip lines, *EF* and *IJ* are potential slip surface, *B* area is the scope of loading. If excavation work is conducted on the side next to D point, GI would drift towards the left side.

2.3. Horizontal displacement calculation models in loading process

So far, sound theoretical results have been achieved in terms of calculating method for lateral displacement at any point within the area. For instance, under the effect of concentrated force, Boussinesq's Solution (Fu et al., 2012) writes like

$$u = P(1+\mu)[xz / R^3 - (1-2\mu)x / (R^2 + Rz)] / 2\pi E \tag{2}$$

In the formula, *u* (mm) is lateral displacement at any point within the area; *P* (kN) is concentrated force in vertical direction exerting an effect on the origin of coordinates; *R* is the distance from any point to the point influenced by concentrated force, $R = \sqrt{x^2 + y^2 + z^2}$; *r* is the horizontal distance; *E* (MPa) is elastic modules of soil mass and μ is Poisson's ratio.

Since outer dumps normally assume a rectangular shape, the lateral displacement at a certain point beyond the dump scope is calculated using the formula hereunder:

$$u(z)=\iint\limits_{F} du=\frac{P(1+\mu)}{2\pi E}\int_{-\frac{b}{2}}^{\frac{b}{2}} dy\int_{-\frac{l}{2}}^{\frac{l}{2}}\left[\frac{(L-x)z}{R_1'^3}-(1-2\mu)\frac{(L-x)}{R_1'(R_1'+z)}\right]dx \tag{3}$$

where $R_1' = \sqrt{(L-x)^2+y^2+z^2}$, P (kN) is equivalent uniform live load generated by rectangular waste loading; l and b (m) are respective side length and the other parameters remain the same as Formula (2).

All the above theoretical results have laid a solid foundation for further study. Furthermore, with the aid of computer program development system, it is feasible to realize batch calculating. However, in addition to lateral displacement, the geotechnical practice has triggered the occurrence of tri-directional displacement (Li et al., 2009) as well. Once the waste rock piles up in the dumps, the scope of valid influence and some key factors as well as the quantitative relations among them are not clearly defined. To discover the according functional relationship, FLAC^{3D} software is used herein to simulate dynamic loading process in outer dumps and record data concerning surface displacement (Benmebarek et al., 2008; Xu et al., 2011), which are then used to draw a regular pattern by means of mathematical treatment.

3. Displacement simulation within the areas for excavation and loading process

3.1. Model establishment

To discover the regular pattern concerning the influence that excavation and loading process has on strata movement, based on basic mining procedure and dynamic simulation, the coal mining and dumping structure layout in a certain open pit is shown in Fig. 3.

The opencast stope is located in the center with Dump No. 1 and No. 2 lined symmetrically on the two sides. Waste is dumped into Dump No. 1 and then No. 2. The final geometrical dimension of the stope is the maximum excavation depth of 120 m, a pit bottom width of 60 m, working slope angle of 18°, non-working slope angle of 22°, end slope angle of 40°. As to the dumps, their base dimension is 542×316 m^2, the final dump height 100 m, and the overall slope angle is 30°. A total of 77 monitoring points were laid out with a space of 50 m in the four major directions around the stope and outer dumps. The physical and mechanical parameters of in situ rock mass and waste dumped in the mining process in listed in Table 1.

TABLE 1

Physical and mechanical parameters of rock mass

Lithology	**Bulk density γ / kN/m^3**	**Cohesion force C / kPa**	**Internal friction angle φ / °**	**Elastic Modulus E / MPa**	**Bulk modulus S / MPa**	**Poisson's ratio**	**Strata thickness /m**
loess	19.5	45.1	29.5	80	6.67×10^7	0.3	20
gritstone	22.4	130	32	8178.27	9.74×10^9	0.36	40

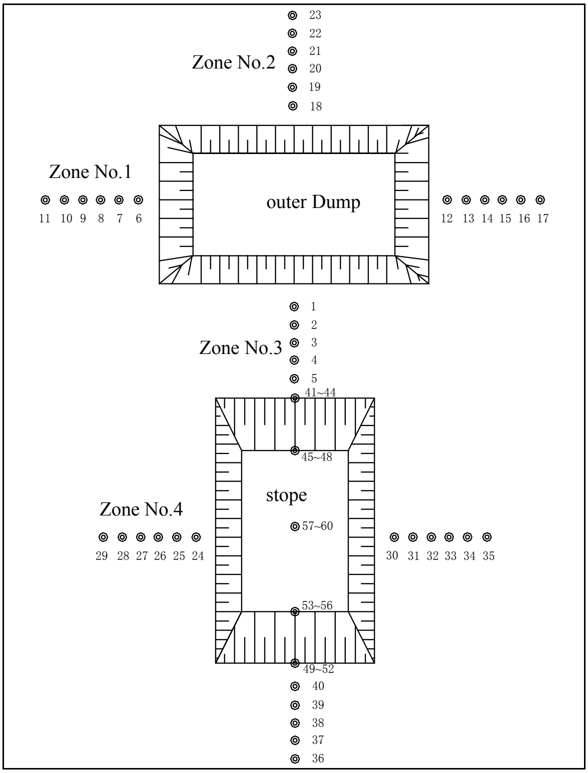


Fig. 3. Coal mining and dumping structure layout in an open pit

mudstone	22.4	127.5	30	15655.89	9.00×10^9	0.21	40
coal	14	185	35	10123	8.03×10^9	0.29	20
medium sandstone	22.7	150	31.5	16101	7.89×10^9	0.16	100
waste	18	30	23	80	6.67×10^7	0.3	100

3.2. Stress unloading features

On the basis of strata's physical and mechanical parameters and open coal mining order, we simulate the process and record unloading features of unbalanced stress as well as displacement pattern at feature points. The in situ strata are divided layer by layer with an average thickness of 20 m. As mentioned above, the excavation goes all the way downward to the coal seam floor, reaching a maximum depth of 120 m. Fig. 4 is about the maximum unbalanced stress curve within the stope area in excavation only process.

As indicated in Fig. 4, when mining depth increases, the unbalanced stress in end slope area assumes a linear growth, which follows a regular pattern ruling slope excavation and unloading. As coal mining goes deeper and reaches a depth of over 80 m, the maximum unbalanced stress ceases to follow the linear pattern. Because the stope is like an inverted prismoid, which means

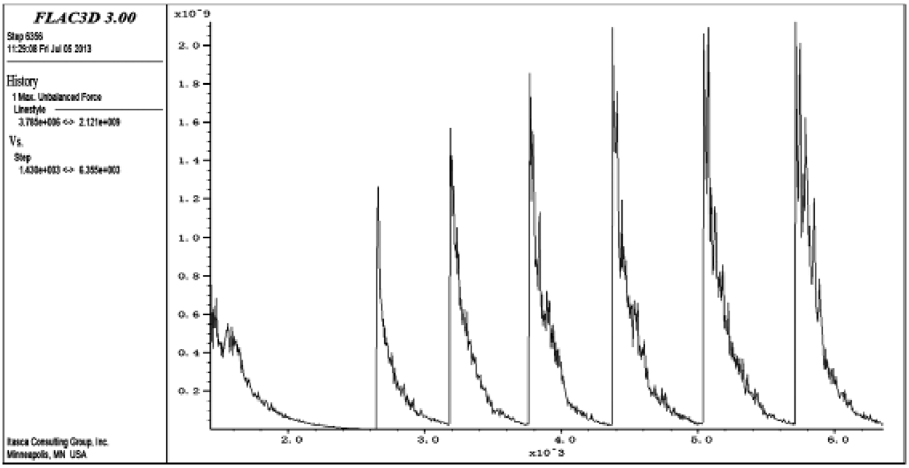


Fig. 4. Unbalanced stress curve inside stope area in excavation process

that the exposed area in lower end slope decreases gradually and also does the free space for unbalanced stress unloading. In other words, when H exceeds 80 m, the maximum unbalanced stress F_u remains basically unchanged. The earthwork volume produced in mining process is entirely transferred onto the outer dumps layer by layer with a varying depth of 20 m, 40 m, 80 m and 100 m. The maximum unbalanced stress curve in excavation and loading process is basically in line with that in excavation only condition.

3.3. Displacement variation pattern

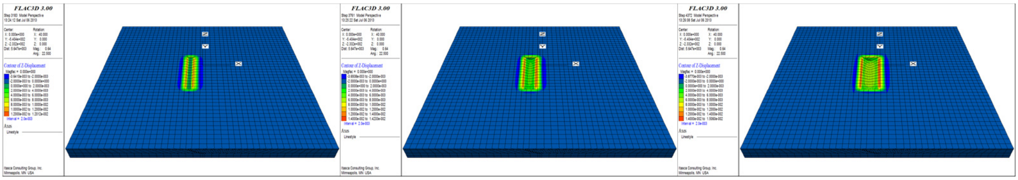
3.3.1. Excavation condition

Under excavation only condition, displacement in neighboring soil mass is obvious to notice. Actually, as indicated in the cloud picture below, a clear circle comes into being, whose shape is basically in accordance with that of the stope and tends to become larger with increasing mining depth H. The according soil mass displacement at different H is shown in Fig. 5.

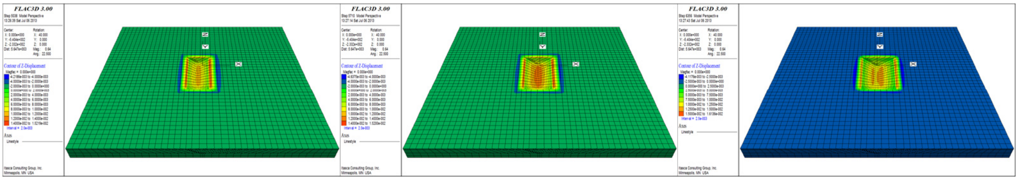
Statistics concerning tri-direction displacement within the scope of influence have been gathered and they indicate that under excavation only condition, the displacement values in X, Y direction as well as their peak values within the scope of influence are rather low, reaching an average level of 10^{-5} m. When it comes to the Z direction, however, there emerge clear rules. Z-Direction curve that records displacement variation at feature points along end slope normal is shown in Fig. 5.

Fig. 6 (a) shows that, under excavation only effect, when H increases, the scope of influence for end slope (Zone No. 3) would enlarge as well; when H is 20 m, there is no obvious influence on the stope; when H reaches 40 m, it would affect areas that are 30 m away from the end slope border; when H is 120 m, the scope of influence is further extended to 300 m away. Based on the above data, a function ($R^2 = 0.9642$) between the scope of influence and mining depth is

$$L = 2.72H - 56.3 \quad (H > 0) \tag{4}$$

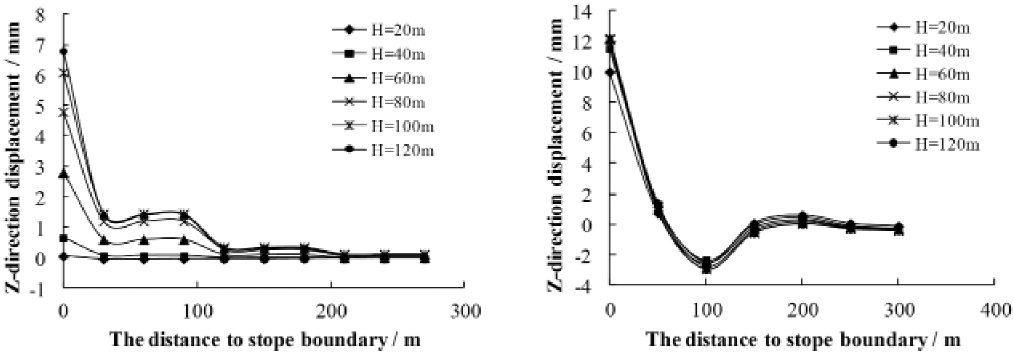


(a) *H* = 20 (b) *H* = 40 (c) *H* = 60



(d) *H* = 80 (e) *H* = 100 (f) *H* = 120

Fig. 5. Soil mass displacement surrounding the stope in excavation condition



(a) Zone No. 3 (b) Zone No. 4

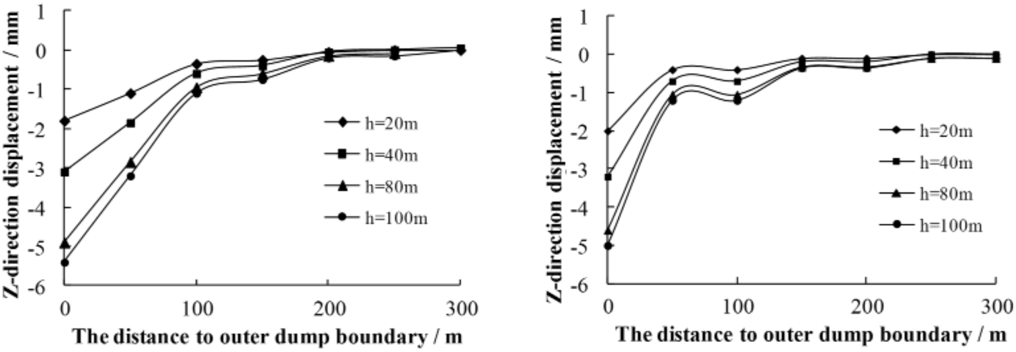
Fig. 6. Z-Direction curve recording displacement variation at feature points along end slope normal under excavation condition

Fig. 6 (b) shows that, as the stope extends downward, rock mass on the side of non-working slope (Zone No. 4) is affected by a certain consistent law. In other words, in spite of different mining depth *H*, its deformation extent and distance affected remain basically the same. As to the Z direction, its peak value reaches 12 mm, and the point that has been most severely affected is around 300 m away from the non-working slope border.

To sum up, a displacement circle takes shape around the stope under excavation only condition, whereas the soil mass beyond the circle remains basically immune to its influence. Specifically, the maximum displacement always falls on the top line of the slope. For instance, for an open pit with a mining depth of 120 m, its scope of influence is 300 m away from the border and the most significant displacement takes place within a range of 0 to 150 m.

3.3.2. Loading condition

Once waste rock mass are stripped away, they pile up on flat ground layer by layer with a changing height of 20 m, 40 m, 80 m and 100 m. Z-direction displacement for points with a different distance away from the dumps is shown in Fig. 7.



(a) Zone No. 1 (b) Zone No. 2

Fig. 7. Z-Direction curve recording displacement variation at feature points along end slope normal under loading condition

As shown in Fig. 7, the surface displacement within the affected area of outer dumps is in general of negative value, as for Z direction curve. That is to say, with load height *h* going up, the value of the geotechnical subsidence increase as well. To be specific, the maximum Z-direction subsidence, –5.8 mm, appears when *h* reaches a value of 120 m. According to the logarithmic function convergence pattern the curve follows, the farther it gets away from the dump border, the smaller Z direction subsidence it would be and finally decreases to zero when it is beyond the influenced scope. As it moves forward, Z direction displacement changes from negative to positive value, meaning soil mass subsiding is replaced by bulging.

3.3.3. Under combined effect of excavation and loading process

So far, we have discussed displacement variation pattern under excavation only and loading only condition. Based on that, we then simulate the according pattern under their combined effect, as shown in Fig. 8.

As can be seen from Fig. 8, the displacement value is constantly changing in the middle region between the stope and outer dump. In detail, bulging occurs mainly on the side close to the stope whereas subsidence displacement is common on the other side close to the outer dump, which increases with growing mining depth and loading height. Specifically, soil mass displacement is abnormal when it is 100 m away from stope border (200 m away from the outer dump border), which results from combined effect of excavation and loading. What’s more, the displacement value at this point continues to go up at a velocity of 0.0228 mm/h. After years of accumulation, it would reach 1m or even meters, bringing about a negative influence on surface buildings and their evenness.

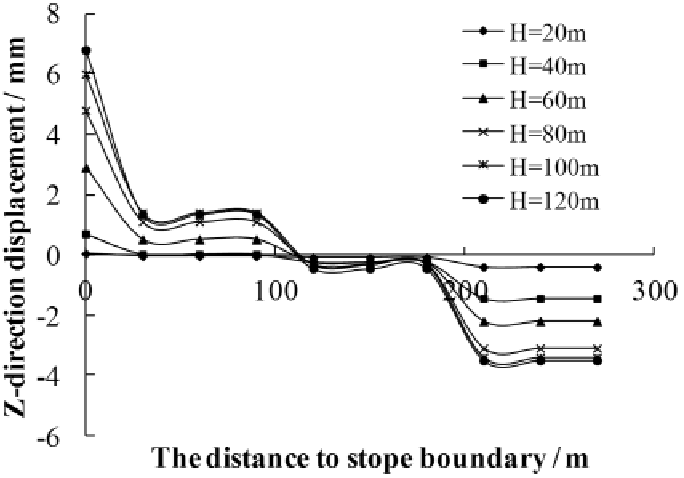


Fig. 8. Vertical displacement curve of feature points in middle region between the stope and outer dump under combined effect

It is highly suggested that sites selected for neighboring surface buildings be kept away from displacement circle so as to prevent relevant base inclination or collapse accidents. When it comes to outer dump position selection, however, in addition to delivery distance, it is vital to calculate soil mass displacement under combined effects of excavation and loading and make an analysis about composite slope stability for the sake of safety in overall stope and outer dump slope area. Z-direction displacement in stope border would gradually vanish with continuous stress unloading. But for the middle region between outer dump and stope, its displacement would develop with time passing by. Also, soil mass deformation and lithological degeneration mechanism there would become key factors in controlling composite slope stability in open pits.

4. Conclusions

Coal seam occurs horizontally and is therefore mined region by region in deep large-scale open pits. Based on the fundamental mining procedure, a mechanical unloading model in excavation process is set up and it is discovered that the unloading strength goes up with increasing mining depth in a linear fashion. Meanwhile, another mechanical model for rock mass loading is established and formulas to work out lateral displacement are provided herein.

By dynamically simulating the coal mining and dumping process in open pits, we have recorded data regarding unbalanced stress and tri-directional displacement at feature points inside the regions and drawn the following conclusions. On one hand, the unbalanced stress enhances with increasing excavation depth linearly. On the other hand, for a stope of 120 m's depth, its 3D unloading peak value remains basically unchanged when H exceeds 80 m.

A displacement circle takes shape around the stope under excavation only condition, which enlarges with growing mining depth. By using fitting method, we have obtained the functional relationship between the two factors, namely $L = 2.72H - 56.3$. As the excavation practice moves downward, the soil displacement pattern on the side of non-working slope remains basically consistent at different mining depths. Specifically, for an open pit with a mining depth of 120m, its scope of influence is 300 m away from the border and the most significant displacement takes place within a range of 0 to 150 m.

Waste rock loading is certain to cause large-scale surface subsidence in neighboring areas. According to the logarithmic function convergence, the closer it gets to the dump border, the higher the dumping is, the greater subsidence would become. As it moves forward to the slope foot, displacement changes from negative to positive value, meaning soil mass subsiding is replaced by bulging.

Under combined effects of excavation and loading, displacement of positive value occurs mainly on the side closer to the stope whereas displacement of negative value is common on the other side closer to the outer dump, which increases with growing mining depth and loading height. Specifically, soil mass displacement is abnormal when it is 100 m away from stope border (200 m away from the outer dump border. What's more, the displacement value at this point continues to go up at a velocity of 0.0228 mm/h. Therefore, it is highly suggested that sites selected for neighboring surface buildings be kept away from displacement circle so as to prevent relevant base inclination or collapse accidents. Meanwhile, it is necessary to conduct displacement computing and composite slope stability analysis.

Acknowledgement

This work was financially supported by the National Natural Science Foundation of China (Grant No. 51034005), National High Technology Research and Development Program of China (863 Program) (Grant No. 2012AA062004), Program for New Century Excellent Talents in University(Grant No. NCET-13-1022). These supports are gratefully acknowledged.

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Received: 29 October 2013