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Research on Time-Space Monitoring, Early Warning Criterion and Failure Mechanism of High Fill Slope Deformation Process in Mountain Region

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ABSTRACT

The deformation of high fill slope in mountain region is currently most exciting topic in geotechnical engineering and also is an unsolved problem. According to monitoring high fill slope sliding and its deformation process of an airport in mountain region, time-space evolution process of this slope was analyzed for the first time. Based on the existing high fill slope projects in mountain region and 18 sets of consolidation-drainage shear tests, time-space evolution characteristics and the warning criterion of deformation rates is given and it also reveals its deformation failure mechanism. The results include: 1) The high fill slope displacement in mountain region is mainly settlement and also it is obvious horizontal lateral displacement. The relative weak interlayer in the filling body or the original foundation generally develops into the sliding face whose front is mild and rear is steep. 2) From aspect of space, the forming and the developing of cracks mainly includes the forming of trailing edge tensioned cracks, the forming of middle flank shear cracks and the forming of leading edge uplift cracks. From the aspect of time, the deformation normally goes through 3 stages which are initial stage, uniform stage and the stable convergence stage. 3) During the normal construction period, it should be paid attention to if the high fill slope deformation speed greater than 0.33mm/d for 3 continuous days and if the speed greater than 0.8-1mm/d for 3 continuous days, it should be warned and take some corresponding measures. If the deformation speed is greater than 20-25cm/d, it is determined that the whole sliding face has connected and the whole slope begins to slide. 4) The samples' deformation and stress state is corresponding with high fill slope temporal and spatial evolution and failure mechanism macroscopically. Deformation firstly happens at the trailing edge and it is always in in a state of damaged area (this area lies behind the “resid” point). The

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deformation develops asymptotically. Leading edge is in a state of before the peak stress and a critical stress state is lying between the leading edge and trailing edge. This achievement can be the reference basis to the high fill slope deformation treating scheme and land slide warning.

1. INTRODUCTION

With urbanization construction and the implementation of “One Belt and One Road” strategy in China, the contradiction between supply and demand of land is becoming more and more increasingly unprecedented. In Lanzhou, Yan’an, Shiyan and many other cities, the scale of land reclamation is unprecedented and all those projects have certain achievement as well as some new technology, theory and engineering problems (Cao, 2011; Li *et al*., 2014; Song, 2013). Especially the construction project of high fill airport in mountain region often has the situation of short life caused by instability and differential settlement such as two landslides of light belt areas in Sanxia Airport (Lin,1997), the west runway landslides in Yunnan Lijiang Airport (Ding 2004), the landslides in an airport in Guizhou (Liu *et al*., 2007), several landslides in Panzhihua Airport (Jiang, 2003; Gu, 2001) and Liuliang Airport landslide, which all challenges the scientificity of mountaintop-removal and gullies-filling strategy. The reason for that problems are that normally the study for high fill slope focus on natural side slope and excavated slope (Herrera *et al*., 2009; Huang, 2007; Quentin B., 2011; Wang, 2005; Zhu *et al*., 2015)but there are not enough research about problems of slope deformation and changes or evolution law of slope stability. For now thorough early warning and judging standard for slope stability and instability failure is unconfirmed. Even though Geeralt (2009), Fernández-Merodo (2014), and Chang (2015) etc. adopted the visco-elasticity plasticity finite model and visco-plasticity constitutive model based on Perzyna theory to reveal the reason and pattern of creep of large-scale creep slope and get creep failure characteristic and mechanical behavior.

However, because the high fill construction has the great height differences, the complex engineering geological and hydrogeological conditions, massive filling and excavation earthwork, many impact factors, uncertainty and complexity of deformation failure, it is difficult to use the method abovementioned to control and forecast slop deformation failure and landslide precisely.

The existing criterions that estimate high fill deformation mostly are given by the expert’s experience (Cao, 2011; Ma *et al*, 2016). For the duration and critical value of displacement rates on different stage, the systematic research is rare. Considering deformation is the most direct response for the high fill slop stability, therefore real-time in situ monitoring for high fill project along with construction process undoubtedly has scientific significance and high engineering value to implement scientific and effective evaluation, monitoring and warning to this kind of slope (Take *et al.*, 2004; Zhu *et al*, 2015). Thus, based on monitoring report of the slip and deformation process of some high fill embankments in an airport, this paper concludes spatiotemporal evolution rules of high fill embankment and combines the related information about the crack developing characteristics and reasons on different stages of existing mountain areas high fill airports in China. In that way, time-space evolution characteristics and the warning criterion of deformation rates is given and it also reveals its deformation failure mechanism. This achievement can be the reference basis to the high fill slope deformation treating scheme and land slide warning.

2. OVERVIEW OF A HIGH FILL AIRPORT IN MOUNTAIN AREA

For a high fill airport in mountain area, the geological exploration from top to down shows the original foundation consists of ①mool and fill stratum (Q_4^{ml}); thickness is 0.1-2.3m; ②silty clay stratum(Q_4^{dl+pl}); burial depth is 0.1-2.3m; the thickness is 0.2-29.4m. Silty clay is deleted in part at the mountain top zone and varies with topography change; ③strongly weathered mudstone stratum(N_2); burial depth is 0.1-30.2m and the burial depth gets shallower from the top to down. Some local areas at mountain top, bedrock exposes; ④moderately weathered mudstone stratum(N_2); the burial depth of underground is about 2.7m-11.0m and the underground water is the quaternary system pore phreatic water , which spreads the both sides of ridge and low-lying parts of valley. The underground water is also rich in middle and lower part of silty clay layer.

The designed length of the runway of the airport is 2800m, and the width of it is 48m. The runway field is fluctuant and changes a lot. The field needs deep digging and high filling massively, hereinto there are 15 filling embankment slopes whose filling height is higher than 20m. The highest filling embankment slope is $^{\#}1$ filling slope (the filling height is about 63m). In each section of slope, the top of the slope aligns level and 1:2 comprehensive slope is used to determine the slope toe; the height of each slope level is 10m; the berm is set every 10m height; there are two kinds of berm-one is 2.5m, the other is 5m. Typical section is shown in Fig.1.

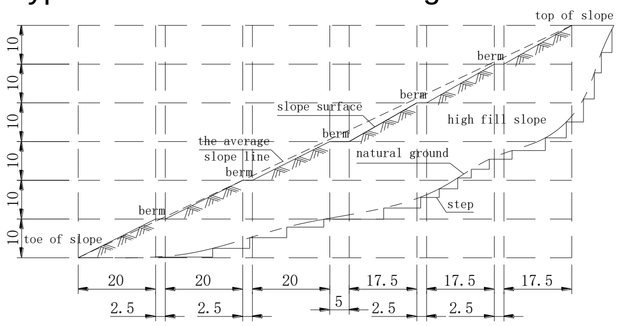


Fig. 1 Schematic diagram of design sectional of high fill slope

The filling material is mainly consists of strongly weathered sandy mudstone and silty clay from excavating areas. In the lower part of soil base area (from the nature ground to the part whose elevation is 1125m and the runway elevation is 1130m), the filling body compactness is 0.93. In the upper part (in the scope of the elevation is 1125m-1130m), compactness is 0.95. In the lower part of soil surface area, the compactness is 0.88 and it in the upper part is 0.93. For fill construction, road roller is used to crush by layer or impact compact the filling body. Every 4 meters high of filling, at the digging filling interface, dynamic compaction is used to strength the soil as reinforcement.

3. HIGH FILL SLOPE LOCAL DEFORMATION PROCESS MONITORING

3.1 The developing process of cracks and its monitoring

(1) #1 high fill slope local deformation monitoring

For #1 landslide area, the slope construct till the height reaches 12.8-13.1m. The gradient is 8°-12° (the natural slope face outsider of the slope toe appears step-shaped). There are lateral cracks appearing at backfill working face stage (the direction which is parallel to runaway direction is lengthways direction). The original foundation lies outside of slope toe of backfill have several longitudinal cracks (the direction which is perpendicular to runaway direction is lengthways direction). As shown in Fig.2, the developing process of cracks is presented below.

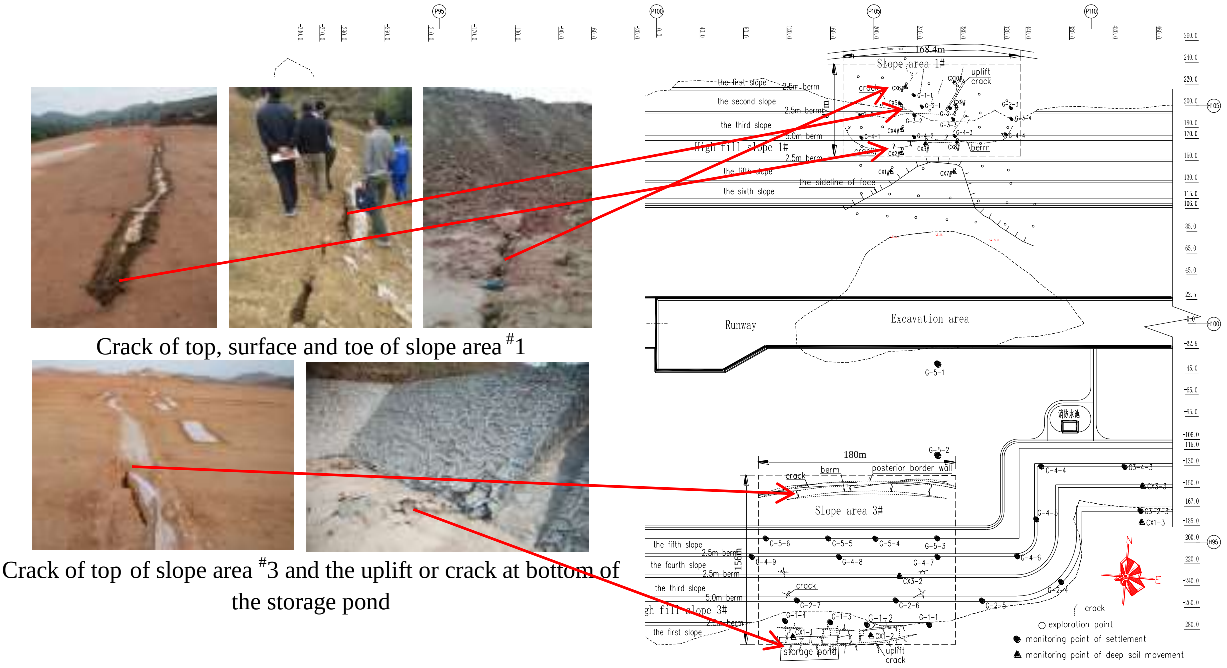


Fig. 2 Layout of high fill slope and the monitoring points

① Backfill working face

On the morning of June 30th, 2014, at the working face of P105+35~P107+25 /H104~H104+8 and whose height is 1093.8m, 70m long and 5mm wide lateral cracks appeared and it extended 27m long to the west by afternoon. The length and width of the crack gradually increased. By the end of October, there are 20 more cracks around the original cracks at the backfill working face. The maximum width is 8-12cm. The maxima height difference between the main crack and trailing edge berm is 11cm.

② Back fill slope

On July 1st, at P106+35~P107+3 slope location, approximate 2cm wide lateral cracks appeared. Some cracks are criss-cross, and the cracks width gradually increases. By the end of October, the cracks width is 7cm.

③ The original foundation at the north of slope toe

On July 3rd, at slope north part, P104+20~P108+5/H104+39~H106+10, whose height is 1084.9m, plough there had 5 longitudinal cracks whose width is 2cm, among which a crack is connected to the longitudinal crack at slope P107+3 location. The width and number of original foundation cracks gradually increases. By the end of October, the cracks width increased by 3-8cm. The maximum width is 10cm. The total number of cracks is about 30.

(2) #3 high fill slope local deformation

On November 2nd, 2014, When the filling height is 4-5m lower than the designed height (the designed height is 40-45m), the deformation at P103~P108/H96+10 area of filling slope suddenly increase obviously. After slowing down construction speed, the slope deformation was under control. On December 2nd, the researchers found storage pond had small cracks on the pond wall near the slop toe. Intermittent cracks which is parallel to runway direction appears and the cracks extended over time and connected locally. On December 23rd, it shows obvious uplift and cavity. Cement sand rendering on the cistern roof develops crushing failure. After consultation, it can be sure that inside the high fill slope body, creep deformation failure had already happened. Therefore, the construction was shut down to prevent large scale landslide disaster. From December 26th to February 1st, 2015, it is rainy and snowy in the area, thus the slope deformation increased quickly at this stage. By the end of April, 2015, the construction of this filling slope has been ceased for monitoring and the shear failure is obvious.

After finding the local deformation of #3 high fill slope obviously increased, displacement, settlement and the deep lateral displacement monitoring is carried out at #3 high fill slope toe, berm and slope top. Layout of the supervision point is shown in Fig.2. In Fig.2, for example, CX1-2 means the 2nd deviation surveying monitoring point of the first level of embankment slope; G-4-8 means the 8th settlement monitoring point of the 4th level of embankment slope; G-DM-5 means the 5th settlement monitoring point on the slope top working face. The article below focus on #3 high fill slope deformation monitoring results and uses it as an example.

3.2 The deep lateral displacement monitoring

(1) 3rd slope berm monitoring at CX3-2

Since November 13th, 2014, the researchers began to monitor the deep layer lateral displacement of CX3-2 in the 3rd berm. Here, the depth of the filling soil is about 17m; the inclinometer pipe is 24m long in total which enters into the original foundation 7m long. Fig.3 shows the displacement of slope soil at different depth variation over time.

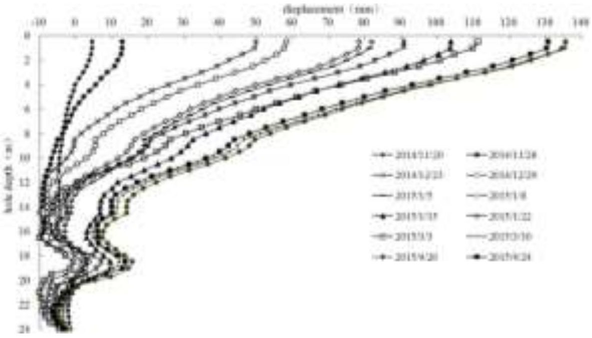


Fig. 3 Monitoring result of slope-direction horizontal displacement of CX3-2

As seen in Fig.3, form the berm surface of 3rd slope (the depth of orifice of deviation surveying hole is record as 0m) to the bottle of filling body (the hole depth is about -17m), the maximum displacement of slope soil appears at the orifice which is about 130.75mm and the displacement reduced rapidly along with deviation surveying hole downward which appears “V” shape-effected by fill loading, not only the obvious the vertical settlement occurs (see in chapter 3.3), but the fill body moved to slope toe as a whole.

The original foundation soil from bottle of fill body to bottle of deviation surveying hole is silty clay. The curve in this section appears “)” shape. At the-19m hole depth, the displacement is maximal and the cumulative displacement is about 20mm which also kept increasing over time. It means inside the filling body creep failure has already occurred. That is because the clay at the bottle of the airport gully has relatively high moisture content and it is the weak layer when comparing with fill body and strongly weathered mudstone. The anti-deforming capability of the clay there is poor. Since October, 2014, the filling construction process was accelerating, when the overlying filling load acted on silty clay layer, pore water pressure among soil grain increase rapidly and had no time to dissipate (pore water pressure monitoring results shown in Fig.4.

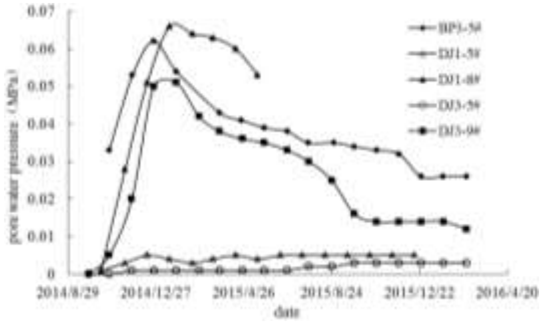


Fig. 4 Monitored results of pore water pressure

BP3-5# pore water pressure gauge is at the bottle of 3rd stage filling slope and in the silty clay layer that 5m under the nature ground. DJ1-5# and DJ3-9# pore water pressure gauge lies 23m higher and 29m higher on BP3-5 respectively in the filling body (Zhu *et al*., 2015). According the monitoring results, during the fast filling and load period, in the original foundation silty clay layer, pore water pressure increased sharply which reached 0.062Mpa, 0.066MP and 0.051MPa respectively. On December 23rd, 2014, after loading was stopped, because permeability of the silty clay layer is poor, pore water pressure dissipated slowly over time. By the end of December, 2015, the pore water pressure is basically stable.

Therefore, under excess pore water pressure and high pressure from overlying fill body, cohesive force among particulate matter of silty clay decreased significantly. When the touch point (face) breaks, the neighboring particles adjust their locations by relatively sliding and rolling and then form new touch point (face) and load path (Mc Dowell et al., 2004). Repeatedly like that, the sliding face is forming in relatively weak layer-silty clay layer. At the same time, strongly weathered mudstone grain is easy to break when encountering water and the grain aggregates expand to volume change. These are two reasons that lead the interface layer of silty clay and strongly weathered mudstone to have creep and sliding deformation.

(2) Slope toe monitoring at CX1-1

On December 22nd, 2014, the researchers found uplift on the bottle of pond and obvious cracks. In order to track and monitor deformation development of soil of the slope toe and decide location of shear opening of sliding plane, deviation surveying hole is set as supplementary. The time-varying horizontal displacement along with soil slip direction of soil from different depth is shown in Fig.5.

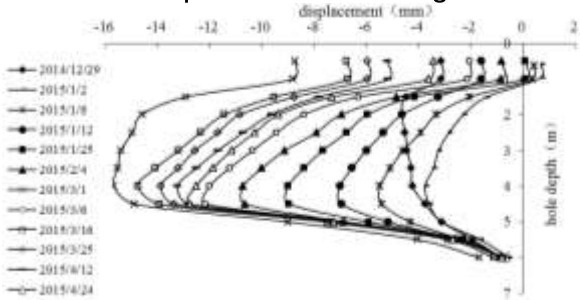
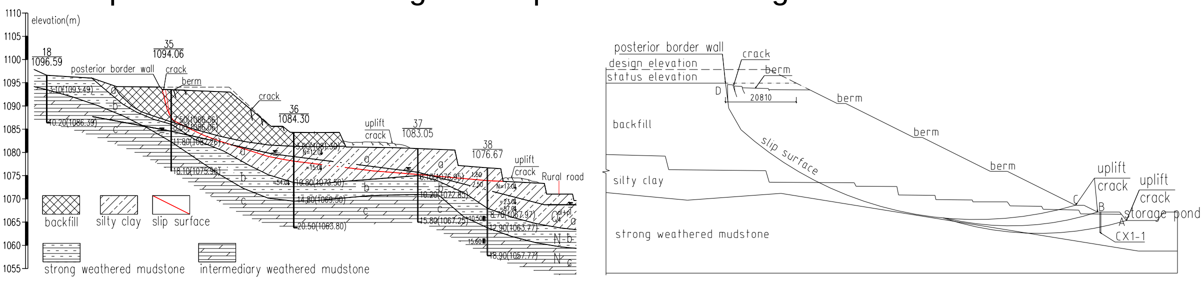


Fig. 5 Monitoring result of slope-direction horizontal displacement of CX1-1

As seen in Fig.5, in the area which is from the ground of slope toe to the bottle of deviation surveying hole, the lateral displacement of soil increases over time and it shows ")" shape. The displacement at a depth of -4m reaches maximum with a total of 16.5mm, which means in this range, under relatively high residual thrust from 1st-5th fill embankment, soil body develops creep deformation. The results abovementioned in concordance with the deformation location of original foundation silty clay layer which is monitored by CX3-2 (section of 17m-24m in Fig.4) of 3rd slope berm. But what is different is the CX1-1 deviation surveying hole of slope toe is resisted by the pond (the pond bottle and wall has several serious bump and cracks); as seen in Fig.6, in the range which hole depth is 0m-2m, the deformation of soil body is obviously smaller than the deformation of soil body in the range which hole depth is -3m-4.5m. With creep deformation value of 1st-5th fills embankment becoming larger and the deformation and thrust passing forward, when the soil body is resisted by anti-sliding segment, in the block parts, stress concentration is generated, which explains why the ground of slope toe has several cracks and the bottle and the wall of the pond has bumps and cracks; when slipped resistant force is smaller than sliding force, the parts has cracks and bumps run through and become shears opening. After tracking and monitoring, the researchers found out that the plump and ringent cracks of slope toe A appear fan shaped which has characteristics of landslide frontal part (Wang, 2005).

(3) Confirmation of the sliding face

According to tensioned cracks location at slope top, deep lateral displacement monitoring results, shearing surface depth and the location and characteristics of uplift at slope toe and cracks longitudinal development can be decided. Based on information above, it can be speculated that inside the filling body of landslide area, continuous sliding surface is basically formed. The main sliding part is at the interface of the silty clay layer and strongly weathered mudstone. Conjectural sliding face location in the main slip area of #1 and #3 high fill slope is shown in Fig.6.



（a）sliding surface position in #1 slope area （b）sliding surface position in #3 slope area

Fig. 6 Schematic diagram of sliding surface position

3.3 The slope settlement monitoring

(1) slope top settlement monitoring

There are 6 monitoring points at top working face (4-5m differs from the designed filling height) of #3 slope sliding area (as shown in Fig.2). The curve of settlement value/settlement rates over time is seen in Fig.7 and Fig.8.

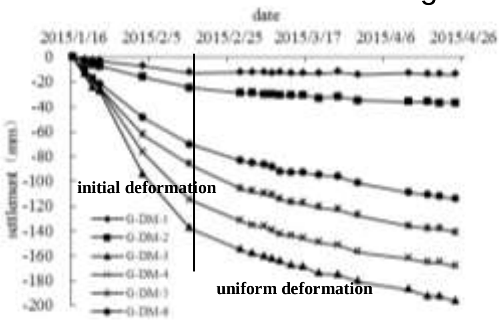


Fig. 7 Time-history curve of settlement on slope top

According Fig.7, since the earthwork was stopped on December 23rd, 2014, from January 6th, 2015 to April 25th, 2015,accumulated settlement value of six monitoring points(G-DM-1~G-DM-6) at the filling body top of #3 slope sliding area is 14.63mm, 37.39mm, 197.07mm, 169.8mm, 141.9mm and 114.9mm respectively. From the spatial dimension, as seen in Fig.6, along with the slope (use D point as boundary and from left to right), the whole filling body settlement increased. The slope rear wall that near the runway (G-DM-1 and G-DM-2) has relative large settlement. G-DM-1 and G-DM-2 respectively has 182.44mm and 159.68mm settlement difference from the settlement of G-DM-3. Berm and obvious cracks are developed at trailing edge of the runway.

That is because effected by the filling load and other factors, the filling body of the landslide trailing edges develops sliding force gradually trumped the anti-slide force provided by corresponding sliding face and the filling body stability decreased. When the stability decreased to a certain degree, considering the middle and back part of fill body is quite steep, the middle and back part develops trailing edge tension stress zone and deformation. The horizontal component of deformation made the fill body at trailing edge develop tensioned cracks which is basically paralleled to slope trend while the vertical component made the fill body at trailing edge develop berm. With the deformation keep developing, on one hand the number of cracks increased and the its range extended, on the other hand, all the intermittent cracks kept extending or connecting to each other and the width and the depth increased, thus, tension cracks was developed at slope trailing edge. Meanwhile, the vertical deformation develops.

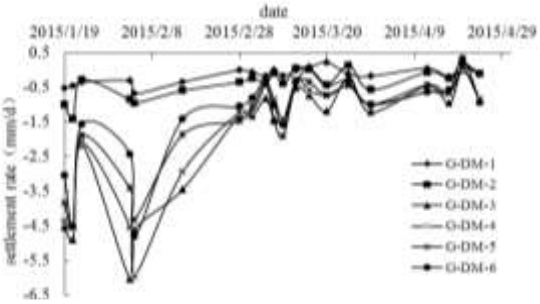


Fig. 8 Time-history curve of settlement rate on slope top

From the aspect of time, as shown in Fig.7 and Fig.8, the slope top settlement process can be divided into two stages. The first stage is initial deformation stage (from January 16th, 2015 to February 15th, 2015). In this stage, the average settlement velocity of sliding mass is 3.5mm/d. the deformation appeared and cracks developed gradually. The deformation curve showed relative large slope but over time, the deformation become normal and the slope decreased. The second stage is uniform speed deformation (from February 15th to April 15th). In this stage, the average settlement velocity of sliding mass decreased by 80% to 0.87mm/d. On the basis first stage deformation, the fill body basically kept deformed with similar velocity. Because constantly affected by other factors, its deformation curve has variability but in this stage, the deformation curve trend is a slant line. Macroscopic deformation velocity remains.

(2) 5m berm settlement monitoring

There are 7 monitoring points on the berm surface. Setting of monitoring points in sliding area is seen in Fig.2. The curve of settlement value/settlement rates over time is seen in Fig.9 and Fig.10.

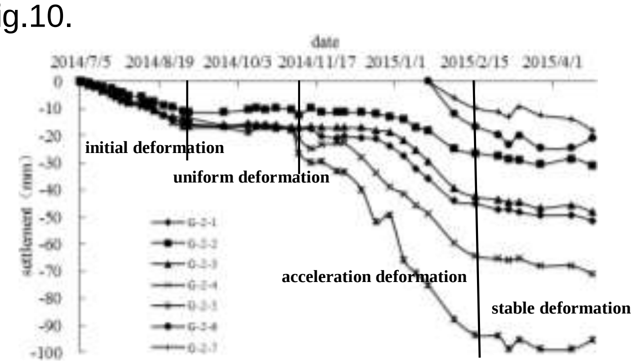


Fig. 9 Time-history curve of settlement on platform of 5m width

Known in Fig.9, from 2014 to July 5th to the end of April, 2015, accumulated settlement value of 7 monitoring points (G-2-1~G-2-7) at the 2nd stage filling slope berm is 51.34mm, 31.18mm, 48.65mm, 71.16mm, 94.58mm, 20.98mm and 21.85mm respectively. The last two points was set later than the rest because the berm was still under construction by then. From the aspect of space, consistent with the reason of deviation surveying results, with trailing edge deformation increased, the sliding deformation and the force that it produced transferred to the middle part of slope body and pushed the middle part to developed sliding deformation forward. When the middle sliding mass slides forward passively, the shear stress concentration appears at both side boundaries. Thus the shear-tensioned cracks were formed at side wing, which explains cracks phenomenon in Fig.6.

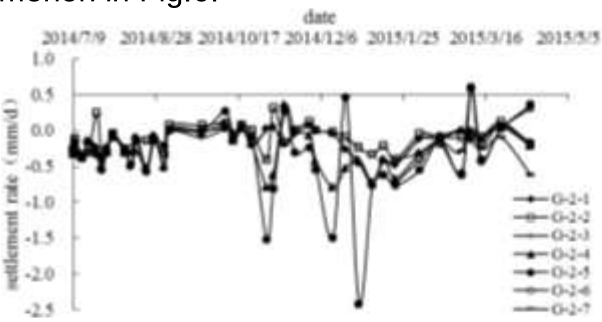


Fig. 10 Time-history curve of settlement rate on platform of 5m width

From the aspect of time, as seen in Fig.9, there are three stages shown in settlement variation curve which is, stable convergence stage, this is because at early stage of filling slope deformation, suitable measure was taken, as shown in Fig.10. The deformation velocity kept decreasing and the corresponding deformation did not increase. If in this stage, the deformation velocity keeps increasing and the curve become steep, it means the slope body enters accelerating deformation stage. Thus the deformation velocity variation in creep deformation process of high fill slope can reflect its situation of stability. In combination with existing settlement and displacement variation rules of airport high fill slope, the advice with significance to control deformation can be provided.

The first stage: initial deformation stage (from January 5th, 2014 to November 7th 2014). In this stage, the average settlement velocity of sliding mass is 0.22mm/d. the deformation velocity is slow. The second stage is uniform speed deformation stage (from November 7th to February 4th, 2015). In this stage, the average settlement velocity of sliding mass was two or three times of velocity at former stage but is relatively uniform at about 0.68mm/d. The settlement value is 26.82mm. The reason is that from the end of October to early in November, due to continuous rain, plus temporary drainage measure of construction is not appropriate. There is local waterlogging and infiltration at the top working face and sliding force increased. The temporary drainage ditch at slop toe drain poorly. The infiltration water made anti-slide force decrease. After reformation, because the slowing down construction speed measure was taken in early November, settlement velocity had been decreased to 0.33mm/d by the end of November. Since December, the weather condition improved, the construction speed increased obviously and the settlement velocity increased again to 1.2mm/d averagely. The 3rd stage: stable convergence stage (from February 4th to the end of April). In this stage, the settlement vale of sliding part is 6.99mm and the deformation velocity decreased to 0.088mm/d. The berm surface settlements become to have convergent tendency.

(3) Slope toe settlement monitoring

#3 slope sliding area had 4 monitoring points in total, seen in Fig.2. The curve of settlement value/settlement rates over time is seen in Fig.11 and Fig.12.

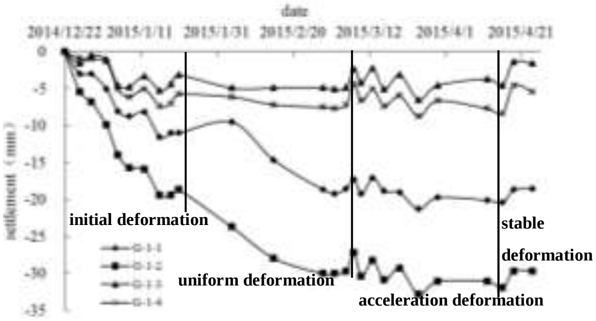


Fig. 11 Time-history curve of settlement at slope toe

According Fig.11, accumulated settlement value of G-1-1~G-1-4 is respectively 18.35mm, 29.6mm, 1.43mm, and 5.4mm. The settlement of G-1-1 and G-1-2 is greater than G-1-3 and G-1-4 which is consistent with the settlement deformation at every stage berm and slope top. From the aspect of space, during the process of 1st ~5th stage fill slope crept forward, the load transferred. The formation of shear opening caused by heave cracks at leading edge is the same with that at CX1-1 which is typically artificial loading “back pushing” slide whose slide face is mild at front and steep backward.

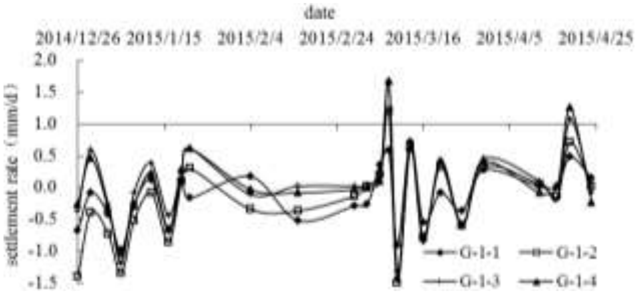


Fig. 12 Time-history curve of settlement rate at slope toe

From the aspect of time, slope toe settlement variation curve also has three stages: initial deformation stage, uniform deformation stage and stable convergence stage. The Fig.12 shows that the settlement variation curve is seriously affected by rapid loading and rainy and snowy weather. The maximal settlement rate is about 2mm/d.

4. WARNING CRITERION AND FAILURE MECHANISM OF HIGH FILL SLOPES

4.1 Space-time evolution characteristics and early warning criterion in different deformation stages

High fill slope is formed by compaction layer by layer and backfill and the filling body is a medium for subsidence and the load for lower soil layer, its deformation characteristics and the law is determined and controlled by the damage mechanism of slope body which has been mentioned before. Currently accurate control and forecast high embankment deformation and landslide is difficult. However, in the process of creep, crack and deformation of the different parts of high fill slope is the most intuitionistic macroscopic characteristics of whether landslide starting or not and the development evolution. High fill the airport of slope deformation monitoring data shows that the deformation has the characteristics of timeliness (creep phenomenon) and under the condition of stress is not very high, it can produce large deformation; When lack of monitoring data, through the accurate identification of fracture development characteristics, it would be simple and effective for high fill slope deformation evolution analysis. Typical characteristics of high fill slope deformation failure on different stages of the typical are shown in Tab.1.

Tab. 1 Crack and macroscopic characteristics of typical high fill slope in different deformation phases

Landslide name	The deformation reasons	The initial stage of deformation	Uniform deformation stage	Stable or accelerate convergence deformation stage
Yichang three gorges airport landslides (Lin, 1997)	The original gully 0.4 ~ 1 m thick residual sludge layer, a lot of rain	Backfill soil after more than 8 m rear tension cracks appeared	The sliding body more visible place with the main sliding direction of central vertical and oblique shear fractures and concave ground with the berm	Ballooning belt and cut out clearly, in the front sliding rate of 20 ~ 50 cm/d, slide the volume 13.4 x 104 m3, 165 m of slip line
Jiuzhai huanglong airport creep (Liu, 2006)	Top loading too fast Rainfall infiltration	The rapid development of horizontal displacement, the displacement is 0.083 ~ 0.114 cm/d, displacement rate is 2 ~ 6 cm/months	Displacement changes gently, day displacement is less than 0.003 cm/d, displacement rate is less than 0.77 cm/months	Stable convergence displacement is 5 ~ 29 cm
Guizhou a landslide at the airport (Liu, 2007)	At the bottom of the viscous soil compression deformation is too large	Trailing edge cut piece, lateral shear cracks, central cave in a small scale	Trailing edge's jagging is obvious , leading edge hunch cracks, displacement rate is 0.01 m/d.	7 d sink within 2.53 m, displacement rate is 0.2 ~ 0.32 m/d, landslide running is 112 m, trailing edge 155 m wide, vertical is 8 m.
Panzhihua airport 12 # landslide (Gu, 2011)	The effect of groundwater and rainfall	New cracks distribute in the top of slope, a single length is 15 ~ 20 m, monthly cumulative displacement less than 28 mm	Front retaining wall was force deformation, deformation rate is less than 5 mm/d, The rain period cracks in the resurrection.	Critical deformation rate is about 450 mm/d, landslide span is 1600 m, width is 200 ~ 400 m, the thickness of 10 ~ 25 m
Luliang airport landslide (Ma, 2016)	The original foundation loess deformation is too large	There are three main cracks gradually appeared in slope , displacement rate is 0.3 ~ 2.4 mm/d.	The lower part of slope body generate shear opening, crack length increasing, the longest extension is 82 m, the displacement rate is 0.01 ~ 0.03 m/d	The vertical spacing on both ends of the ground of cracks is 2 ~ 8 cm, the horizontal crack width ranging from 4 to 15 cm, stable convergence displacement is 7 ~ 23 cm
The 1 # landslide at the airport	Compression deformation of silty clay layer of the original foundation is too large, the rainfall infiltration	Trailing edge slope generate tension cracks and extends rapidly and the deformation rate is 0.3 ~ 1 mm/d	Side shear fractures, frontal uplift cracking phenomenon appeared and deepening, the rain period deformation are increased, cracks on the deformation is 2 ~ 3 cm per month	Crack develop into arc tensile circle, tend to be connected, crack about 8 ~ 12 cm wide, berm about 11 cm high
The 3 # landslide at the airport	Top of slope loading too fast, compression deformation of silty clay layer of the original foundation is too large	Trailing edge slope generate tension cracks, there were signs of new extension deformation, deformation rate is 0.22 ~ 3.5 mm/d	Trailing edge cracks changed rapidly with the construction load, deformation rate is 0.2 ~ 0.87 mm/d	Frontal uplift shear crack phenomenon is obvious, open cracks in 4 ~ 11 cm wide, about 3 ~ 10 cm high camp

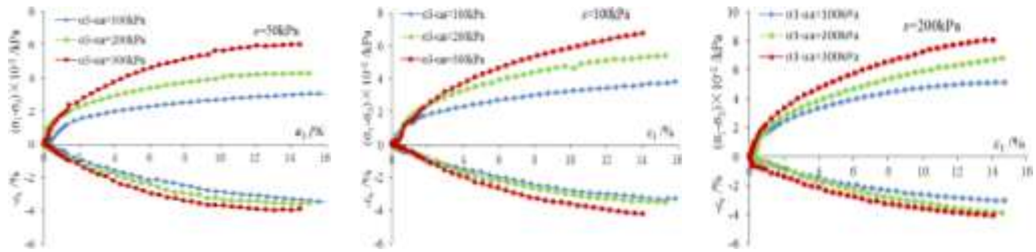
By counting data in Tab.1, the main reasons of mountain airport high fill slope deformation are: the unqualified original foundation treatment, loading too fast, heavy rain or groundwater rising too rapidly. Since the initial deformation appears to stable convergence or instability failure, from the space point of view, crack formation and development mainly includes: trailing edge crack formation, central shear cracks formation and frontal heave crack formation. From the time point of view, it tends to pass through three different stages of deformation which have different evolution characteristics: 1) initial deformation stage, at the trailing edge slope tension fracture is found, and fracture length gets longer and lateral shear fracture appears. The deformation rate is 2~6cm per month and 0.22~3.5mm per day; 2) uniform deformation stage, the trailing edge fell down, and shear fracture appears and at front side drum tension crack is growing. With the deformation in the rain period gets more obvious. if later the deformation rate is stable, deformation rate is 0.03~0.87mm per day, such as Jiuzhaihuanglong Airport #3 landslide area; If later deformation is accelerating, rate of deformation is 1~3cm per day; 3) in the stability convergence or accelerating deformation stage, the circle tensile cracks is gradually formed, and sliding surface gradually cuts through. The cracks is widening, deepening and extending. If the slope is stable, crack is 4 ~ 15 cm wide, berm is about 2~11cm high, and the displacement converges at 5~29cm; If slope slide or are in the slip, deformation rate is 20~50cm per day.

In conclusion, it is suggested that during the normal construction process, the high fill slope deformation rate is greater than 0.3mm/d for 3 consecutive days, in that case it should be alert. When the rate is greater than 0.8~1mm/d for 3 consecutive days, it shall be alert and taken corresponding measures. If the deformation rate is greater than 20~50cm/d, it can determine the sliding surface begins to slide as a whole. It need to start early warning plan to reduce the loss to minimum. In addition, combining with the slope deformation reason, the warning criterion of weak sliding surface existing in the basement is bigger than landslide of rigid sliding surface. The warning criterion of the upper part of the slope is bigger than lower part.

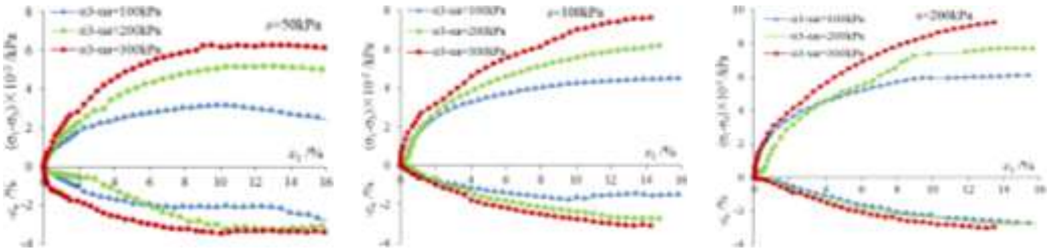
It should be pointed out that for natural slope and excavation slope, deformation rate as landslide stability criterion is a method was discussed widely and applied widely. But there were few analysis reports of high fill slope deformation due to the different projects having different geological conditions and characteristics. The incoordination of internal and surface of slope and the incoordination of different monitoring points, which leads the monitoring results are likely to be very different, therefore, the early warning criterion and the space-time evolution characteristics at different deformation stages of high fill slope need further enrich and perfect.

4.2 Failure mechanism at different deformation stages

For systematically analyzing the reshape mixture material of this high fill slope and studying its strength and deformation characteristics, unsaturated soil triaxial-apparatus is used for 18 matrix suction controlled(50, 100, 200kPa) and net confining pressure controlled(100, 200, 300kPa) consolidation drained shear tests (Fredlund, 1993). The compacting factor n is 0.88 and 0.93. Considering the soil sample is similar to the filling material as much as possible, so the packing earth-rock ratio m is 4:6, and its w_P =18.1, w_L =23.7, $\rho_{d\max}$ =2.03 g/cm^3 and w =10.4. The samples in the condition of suction and net confining pressure are controlled to be constant. The $(\sigma_1-\sigma_3)\sim\varepsilon_1$ curve in the process of triaxial shear test is shown in Fig.13.



（a）n=0.88



（b）n=0.93

Fig. 13 Relationship curves of $(\sigma_1 - \sigma_3) \sim \varepsilon_1$ and $\varepsilon_v \sim \varepsilon_1$ of m=4:6 soil samples

Lateral comparison from Fig.13 shows that when compaction factor of soil samples is the same, under the same suction, if net confining pressure is greater, the strength of the sample is greater and volume change gradually from the shear shrinkage converts to dilatancy. When they have the same net confining pressure, if the suction is greater, the strength is greater and volume change is greater. It shows that suction has important influence on strength of soil sample and its volume change.

By longitudinal comparison, the sample who has the same net confining pressure, the suction and the same mixture ratio, if the compaction coefficient is higher, the strength of specimen is greater. Strain curve gradually convert to the ideal elastic-plastic model from strain hardening type. Some soil sample under low net confining pressure tends to be strain softening model, and under the higher the compaction factor, softening phenomenon is more obvious, but overall softening is not obvious.

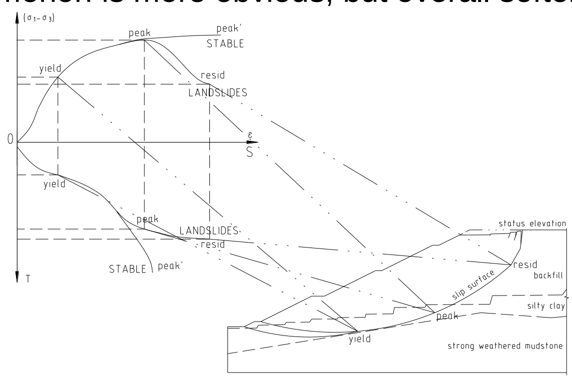


Fig. 14 Relationships among destabilized process and time-space evolution of high fill slope

Although space-time evolution characteristics of different high fill slopes are different, but its essence is shear damage in rock and soil mass. The shear deformation is related to the sliding surface properties. Based on the analysis above, as shown in Fig.14, mountainous area high fill slope deformation time-space evolution and failure mechanism are: 1) in the normal construction process, before strength of soil at the trailing edge of fails to reach the yield status, slope deformation should be finished in a short time. The value mainly depends on the filling body resistance and the filling load. In theory, there will be no cracks; the accumulative deformation would not exceed the experience value in table 1. 2) when entering the stage of initial deformation, the stress of slope body makes original pore shut or nearly shut. Granules contacting area increases, and the trailing soil strength constantly reinforces, which is generally less than the peak state (peak), at the same time, the yield state of slope moves down along the potential sliding surface; At this point, the soil at trailing edge which reaches the yield point has cracks first, and macro deformation characteristics begin to strengthen. Now some measures can be taken according to warning deformation rate above mentioned, which is most effective and reasonable. 3)when getting into the uniform deformation stage, the slope stress changes constantly; the soil presents a hardening effect; the strength of trailing edge soil is in the peak state approximately. The yield situation (yield) of slope continues to move down along the potential sliding surface; the cracks at trailing edge of this stage constantly extend and increase; shear cracks appears at flange; the leading edge hunches and fracture. At this time, according to the deformation warning rate above mentioned, some measures should be taken quickly. Generally, it can avoid the deformation of slope entering into the acceleration phase. 4) if the measures is taken correctly in the initial and uniform deformation stage, there is still a hardening effect inside the slope; the slope deformation goes into stable convergence stage. stress state of each point and the, width and quantity of cracks on the potential slip surface remain basically unchanged. Some cracks tend to be closed; If slope stress increases further in uniform deformation stages, hardening effect disappears; the initial yield and peak state soil significantly tend to peak and resid state respectively, at the same time, each point goes down along the potential sliding surface; cracks extend intensively. The trailing edge berm and frontal uplift phenomenon is obvious; the sliding surface cut through; the deformation rate increases with time which is close to sliding state, until it is destructive. According to the slope deformation warning rate put forward before, early warning plans for safety and disaster mitigation should be initiated. The deformation failure of mountainous area high fill slope develops progressively. The failure occurs firstly at trailing edge, and it is often in a state of post-damaged area(this area lies behind the “resid” point); the part between leading edge and trailing edge is in the state of critical stress.

5. CONCLUSIONS AND SUGGESTION

(1) The mountain area high filling body is sedimentation medium as well as load. The displacement is mainly settlement and also is obvious horizontal lateral displacement. Since the original foundation treatment is not qualified, the loading is too fast, the rain is heavy or the underground water arises, under excess pore water pressure and high pressure from overlying fill body, the relatively weak interlayer inside

the filling body soil or original foundation soil firstly develops into slide face which is mild at front and steep backward.

(2) From aspect of space, the forming and the developing of cracks mainly includes the forming of trailing edge tensioned cracks, the forming of middle flank shear cracks and the forming of leading edge uplift cracks. From the aspect of time, the deformation normally goes through 3 stages which are initial stage, uniform stage and the stable convergence stage. Seizing cracks evolving and deforming rules, it can provide the significant reference for high fill deformation control and sliding warning.

(3) During the normal construction period, it should be paid attention to if the high fill slope deformation speed greater than 0.33mm/d for 3 continuous days and if the speed greater than 0.8-1mm/d for 3 continuous days, it should be warned and take some corresponding measures. If the deformation speed is greater than 20-25cm/d, it is determined that the whole sliding face has connected and the whole slope begins to slide.

(4) When the samples have the same compacting factor and net confining pressure or suction is bigger, the samples volume change gradually converts to dilatancy from contraction. When the samples have the same net confining pressure and suction, if the compacting factor is greater, the strain curve gradually converts to ideal elastic-plastic type from strain hardening type. Under low net confining pressure, some samples become strain softening type.

(5) The samples deformation and stress state is corresponding with high fill slope temporal and spatial evolution and failure mechanism macroscopically. Deformation firstly happens at the trailing edge and it is always in in a state of damaged area(this area lies behind the “resid” point). The deformation develops asymptotically. Leading edge is in a state of before the peak stress and a critical stress state is between the leading edge and trailing edge.

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