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Linear regression analysis for factors influencing displacement of high-filled embankment slopes

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Abstract. It is a common failure type that high-filled embankment slope sideslips. The deformation mechanism and factors influencing the sideslip of embankment slope is the key to reduce the probability of this kind of engineering disaster. Taking Liujiawan high-filled embankment slope as an example, the deformation and failure characteristics of embankment slope and sheet-pile wall are studied, and the factors influencing instability are analyzed, then the correlation of deformation rate of the anti-slide plies and each factor is calculated with multivariate linear regression analysis. The result shows that: (1) The length of anchoring segment is not long enough, and displacement direction of embankment and retaining structure are perpendicular to the trend of the highway; (2) The length of the cantilever segment is so large that the active earth pressures behind the piles are very large. Additionally, the surface drainage is not smooth, which leads to form a potential sliding zone between bottom of the backfill and the primary surface; (3) The thickness of the backfill and the length of the anti-slide pile cantilever segment have positive correlation with the deformation whereas the thickness of anti-slide pile through mudstone has a negative correlation with the deformation. On the other hand the surface water is a little disadvantage on the embankment stability.

Keywords: Liujiawan; sheet-pile wall; high-filled embankment slope; linear regression analysis

1. Introduction

There were many cases of slope failure caused by engineering activities, such as Vajiont reservoir in Italy, Qianjiaping Landslide and the quarry slope in Jinping hydropower station (Sun *et al*. 2013). Cases of embankment failure is are more common, such as, Badu Station Landslide (Wang *et al*. 2008), while the vast majority disasters, which mostly occurred during the constructing period, are unknown because they were dealt with in time and did not cause the casualties. However, the high expense for disposal these disasters should not be ignored.

Researchers focus on the sideslip model and evolution mechanism of embankment slope (Huang *et al*. 2008, Zhang *et al*. 2011, Zhao *et al*. 2013, Han 2013, Wu 2011), it can be divided into three kinds of model by the precipitating factors: simple sideslip, sideslip caused by soft foundation and sideslip between slopes (Gao *et al*. 2004). Shen *et al*. (2012a, 2013) analyzed slope stability using the Generalized Hoek-Brown criterion. To an engineering project, the effective protection measure is mostly significant (Wang 2001, Ashour *et al*. 2004, Smethurst and Powrie

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Fig. 1 The full picture after the engineering completion

2007, Won *et al*. 2005, Strat a Systems Inc. 2000, Anastasopoulos *et al*. 2010, Vahedifard *et al*. 2012). There are many cases of treated slopes failure, especially embankment slopes. However research on these failure cases is rare. Liujiawan High-filled Embankment Slope from 10.022 km to 10.144 km in a highway is taken as an example, the deformation and failure characteristics of this embankment slope and sheet-pile wall are studied, and the influence factors are analyzed. The correlation of deformation rate of anti-slide piles and every influence factor is built up based on multivariate linear regression analysis method, and the impact of different factors to the deformation of anti-slide piles is discussed.

2. Engineering geology condition

Liujiawan, located in a low mountain erosion landform, is a natural slope with an average incline of 16 *degrees* as shown in Fig. 1. There exist two gullies which are intersected at a high-angle with the highway.

Liujiawan is applied with a whole fill integral subgrade, the pavement is 24.5 m wide, and the elevation ranges from 492.6 m to 485.2 m. In order to improve the subgrade stability, 21 reinforced concrete anti-slide piles with 2 m × 3 m section size and 6-meter spacing are designed and situated in the left of the subgrade. Their lengths are 24 m (21#), 26 m (1#, 17#~20#), 28 m (2#~4#, 10#~16#) and 30 m (5#~9#), respectively. Reinforced concrete retaining plates are hung between these piles. There exists a fill slope, a height of 8 meters and a slope ratio of 1:1.50, between anti-slide piles and the pavement as shown in Figs. 2, 3 and 4. The sheet-pile wall was finished in early 2008, and a half year later the subgrade was filled to the designed height.

Due to engineering geological survey and exploration drilling, the stratums of the site contain backfill (Q_4^{me}), the Holocene residual (Q_4^{el+dl}) and sandy mudstone of Triassic middle Badong group (T_2b).

(1) Q_4^{me}: the backfill is formed in the process of building this highway and has become a part of the subgrade, the thicknesses range from 2.3 m to 15.3 m, and it is composed of 70%-85% gravel of mudstone or sandstone with the particle size from 10 mm to 620 mm and 15%-30% silty clay. The dry unit weight of backfill is 19.5 kN/m^3, and the saturated is 20.0 kN/m^3. The cohesion and the internal friction angle in natural are 15

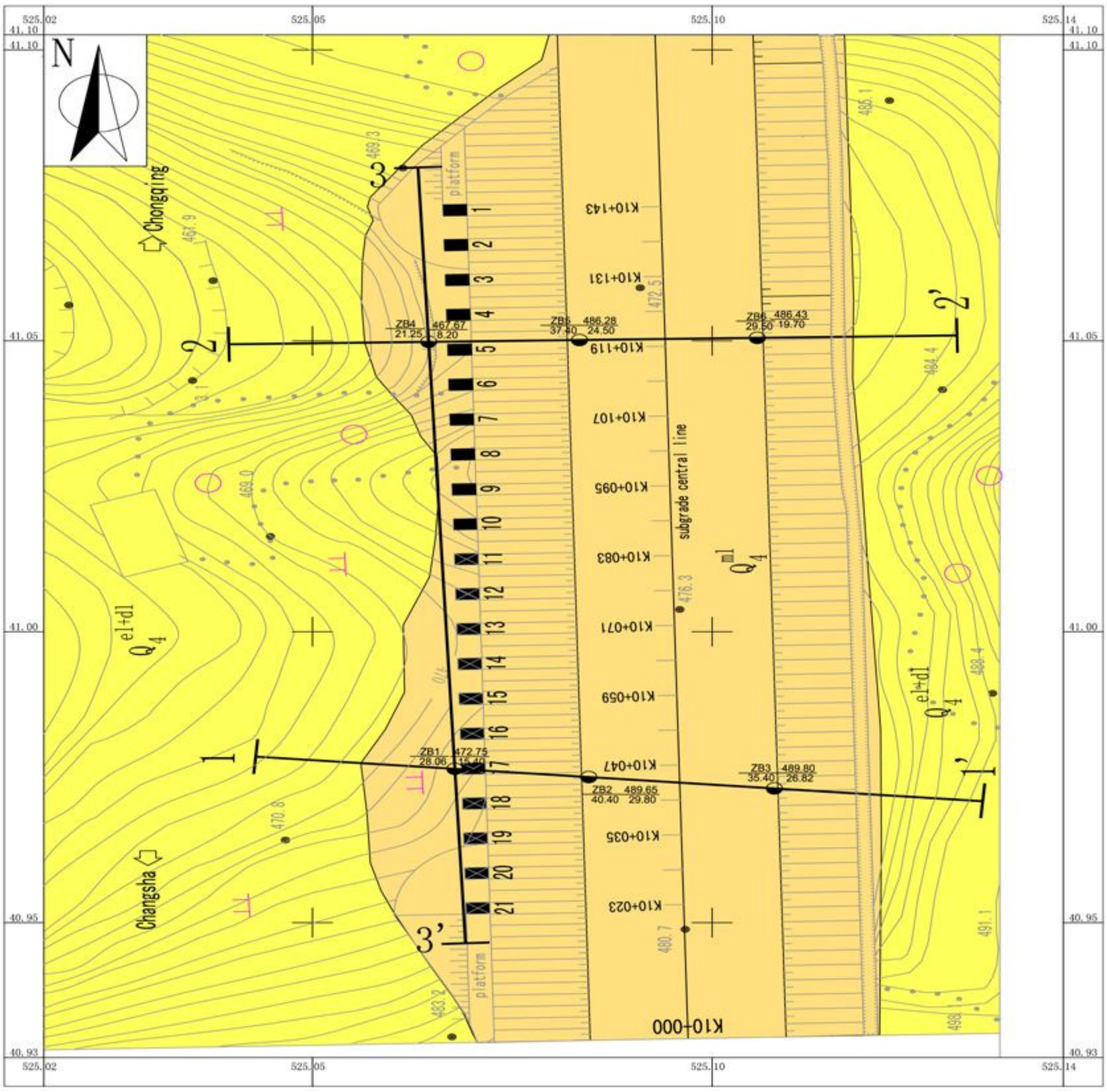

Fig. 2 The layout plan of sheet-pile wall and high-filled subgrade of K10+022 ~ K10+144

kPa and 20 *degrees*, respectively, and that in saturated condition are 10 kPa and 20 degrees.

(2) Q_4^{el+dl}: The thickness of the residual slice ranges 5.70 m to 18.12 m. Its composition is 65%-75% cohesive particles and 25%-35% gravel with the particle size from 10 mm to 130 mm. It is slightly loose, wet and plastic. The dry unit weight of backfill is 19.0 kN/m^3, and the saturated is 19.5 kN/m^3. The cohesion and the internal friction angle in natural are 29.3 kPa and 11.7 degrees, respectively, and that in saturated condition are 21.7 kPa and 10.3 degrees.

(3) The lithology of T_2b is thin layers of mudstone, and its thickness is from 8.58 m to 13.05 m. The dip of the rock formation is 105 degrees and the dip angle is 28 degrees. The

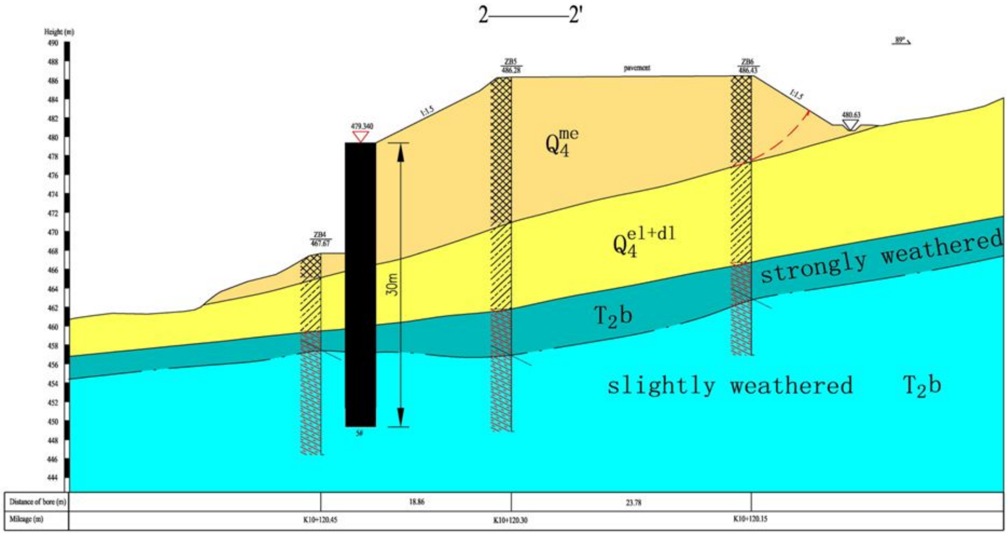

Fig. 3 The anti-slide pile layout section in 2-2' profile

strongly weathered mudstone is crushing with well intensive mesh cracks, mostly thin, soft and low strength. These slightly weathered are mostly integrity, stout prismatic and high strength.

3. Deformation and influence factors

In early 2009, a slightly bulging deformation was found at retaining plates on the left of the embankment, therefore a deformation monitoring in the field had been carried out on the anti-slide piles since March 1st, 2009. Measured data are acquired twice in March, 5th, 2009 and April 6th, 2009. The data shows that, the horizontal displacement on the top of 6#~13# and 21# anti-slide piles were slight, while the displacements on other anti-slide piles were obvious as shown in Table 1. Especially, the accumulated horizontal displacement on 17# anti-slide pile reached 94 cm as shown in Fig. 5. All anti-slide piles deformed mainly perpendicular to the trend of highway without obvious bending deformation or dumping. It explains that the bottom of piles was not fixed successfully.

Beside the displacements, there are some cracks occurred in retaining plates between piles. Several cracks appeared on one side of No. 11 and both sides of No. 12 pile, the included angles of cracks with horizontal plate were about 45 degrees as shown in Figs. 6 and 7. In addition, there was seepage phenomenon after the rain on the retaining plate where exists the crack. These cracks indicate that shear stresses at the bottom of anti-slide pile cantilever segment are large, which lead to destruct the integrity of retaining wall, fortunately it does not go so far as to impact use normally. These anti-slide piles cracked have characteristics of a large active earth pressure, a short cantilever and a little horizontal displacement. It proves that these anti-slide piles at the bottom have the built-in effect so that the crack formed on the large active earth pressure.

In addition, some tension cracks as Fig. 3 also generated along the highway trend on the surface of the right embankment slope.

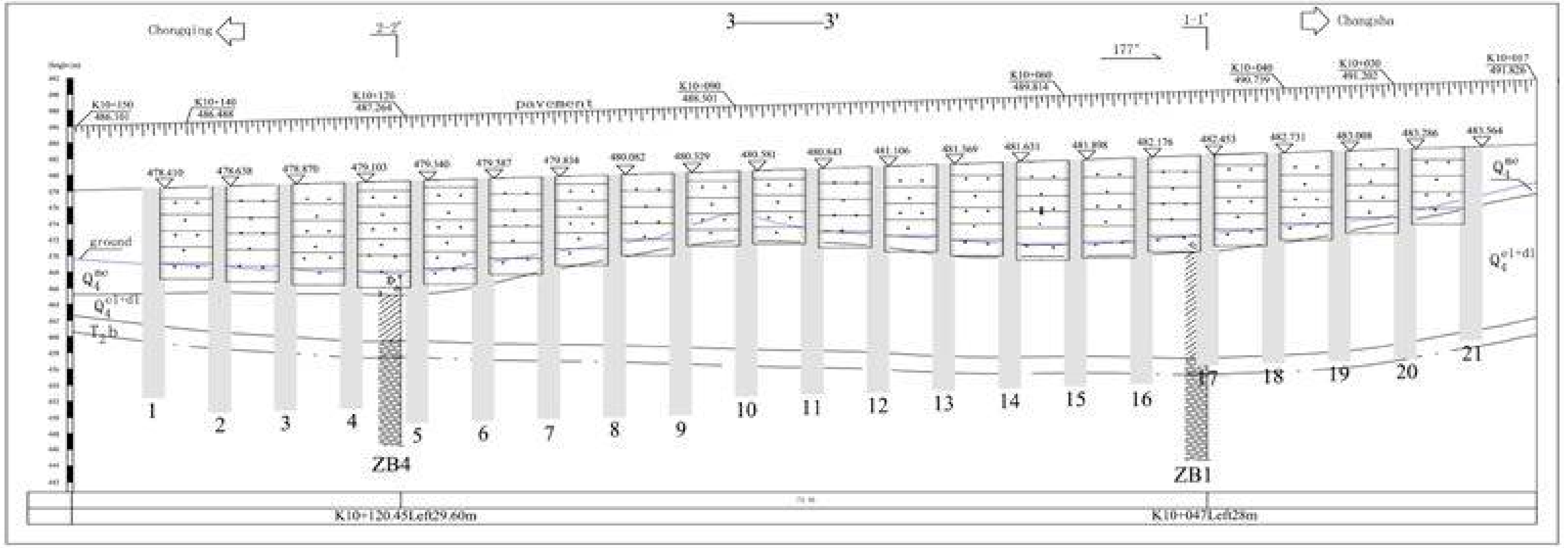

Fig. 4 The elevation arrangement plan of sheet-pile wall in high-filled embankment of K10+022 ~ K10+144t

Fig. 5 The picture after anti-slide pile deformation

Fig. 6 Crack on the lower right side of No. 11 and No. 12 pile

Fig. 7 Crack on the lower left side of No. 12 pile

(1) The primary terrain is a gentle slope, and an amount of backfill was filled on the slope when the highway was being built. In addition, an 8-meter height slope formed between the pavement and the sheet-pile wall, which is the source of a large active earth pressure behind anti-slide piles. The active earth pressures based on Coulomb method are given in Table 1.

(2) Soft rock exists in the anchoring segment and the majority of anti-slide piles are too short to touch the slightly weathered mudstone. As shown in Table 1, except No. 6~No. 13 and No. 21 piles being small displacements, the displacements of the other piles exceed 20 cm. Among No. 1 and No. 5 piles, the maximum accumulated displacement was 44.0 cm on

Table 1 Characteristic, active earth pressure and monitored displacement of anti-piles

Anti-pile No.	Distance to two gullies (m)	Length of anti-pile through various materials (m)					Active earth pressure (kN/)	Displacement (cm)		Deformation rate (cm/day)		
		Cantilever	Fill	Gravel soil	Strongly weathered mudstone	Slightly weathered mudstone		01/03/2009 ~15/03/2009	01/03/2009 ~06/04/2009	01/03/2009 ~15/03/2009	01/03/2009 ~06/04/2009	Total
1#	18.00	9.44	3.70	3.90	2.04	6.92	535.93	0.0	25.0	0.00	1.14	0.68
2#	12.00	10.02	3.27	4.72	2.08	7.91	607.70	6.0	32.0	0.40	1.18	0.86
3#	6.00	10.65	2.87	5.34	2.03	7.11	690.33	12.0	37.0	0.80	1.14	1.00
4#	0.00	11.15	2.72	5.72	2.11	6.30	757.83	16.0	44.0	1.07	1.27	1.19
5#	0.00	11.52	2.51	5.92	2.08	7.98	809.49	10.0	25.0	0.67	0.68	0.68
6#	6.00	10.53	2.64	7.15	2.13	7.55	674.39	6.0	8.0	0.40	0.09	0.22
7#	12.00	9.59	2.00	9.18	2.10	7.13	554.27	0.0	/	0.00	/	0.00
8#	18.00	8.58	1.87	10.77	2.12	6.66	435.42	1.0	3.0	0.07	0.09	0.08
9#	24.00	7.03	2.18	12.47	2.08	6.23	272.66	2.0	/	0.13	/	0.13
10#	24.00	5.51	3.26	13.37	2.04	3.82	137.13	1.0	4.0	0.07	0.14	0.11
11#	18.00	7.54	1.67	13.44	2.04	3.31	323.26	6.0	5.0	0.40	-0.05	0.14
12#	12.00	8.60	1.41	13.15	2.07	2.77	437.45	9.0	/	0.60	/	0.60
13#	6.00	9.36	1.92	12.43	2.06	2.23	526.36	7.0	/	0.47	/	0.47
14#	0.00	10.18	1.62	12.35	2.11	1.75	628.96	19.0	30.0	1.27	0.50	0.81
15#	0.00	10.52	1.43	12.40	2.05	1.59	673.07	34.0	70.0	2.27	1.64	1.89
16#	0.00	10.19	1.85	12.71	2.08	1.17	629.60	33.0	83.0	2.20	2.27	2.24
17#	6.00	9.79	2.15	13.08	0.97	0.00	579.45	34.0	94.0	2.27	2.73	2.54
18#	12.00	9.25	1.98	13.86	0.91	0.00	512.54	26.0	71.0	1.73	2.05	1.92
19#	18.00	8.73	1.48	14.56	1.23	0.00	452.71	13.0	30.0	0.87	0.77	0.81
20#	24.00	7.97	1.03	14.99	2.01	0.00	368.36	5.0	21.0	0.33	0.73	0.57
21#	30.00	6.43	1.19	15.30	1.08	0.00	215.87	5.0	7.0	0.33	0.09	0.19

94.0 cm on No. 17 pile. Compared with their adjacent piles, No. 4 and No. 17 piles both No. 4 pile. Among No. 14 and No. 20 piles, the maximum accumulated displacement was are shorter in the whole and longer on the cantilever segment, and even the latter does not reach the slightly weathered mudstone.

(3) Liujiawan is a low-lying place, where exists two gullies. The surface water is supplied mainly by the seasonal water, secondly rainfall which can reach 200 ton/day when it is rainstorm. However the culvert did not drain effectively and the water at the gullies infiltrated into the fill subgrade, which leaded to form the larger hydrostatic pressure in the inner side of the retaining wall and improved the push behind the anti-slide piles, and also made the touching part between the bottom of the backfill and the primary ground surface becoming a seepage concentration zone of the underground water, where the shear strength became weaken, the stability of embankment decreased.

(4) Joints in the strongly weathered mudstone are such developed. Moreover, it is poor in integrity, low in strength and easily softened with water, which weakened the resistance of the anti-slide piles.

4. Influence factors correlation analysis

The average speeds of every anti-pile in different stages are calculated by the monitored displacements in Table 1. V_{first} means the average speed between March 1st, 2009 and March 15th, 2009, and V_{second} does the average speed between March 15th, 2009 and April 6th, 2009. The speeds of every anti-pile in the two stages are nearly equivalent as Fig. 8. It states that the embankment and piles should be in uniform deformation stage. Therefore we can set up the correlation of deformation rate with some parameters, which are helpful to put forward a reasonable measure.

Multiple regression analysis is much amenable to ceteris paribus analysis because it allows us to explicitly control for many other factors that simultaneously affect the dependent variable. An additional advantage of multiple regression analysis is that it can incorporate fairly general functional form relationships. As we will see, the multiple regression model allows for much more flexibility. In linear multiple regression analysis (Shen *et al*. 2012b), the goal is to predict, knowing the measurements collected on n subjects, a dependent variable $\boldsymbol{y}$ from a set of m independent variables denoted.

$$\{x_1, \cdots, x_j, \cdots, x_m\} \tag{1}$$

We denoted by X the $n \times (m + 1)$ augmented matrix collecting the data for the independent variables, and by $\boldsymbol{y}$ the $n \times 1$ vector of observations for the dependent variable. These two matrices have the following structure.

$$X = \begin{bmatrix} 1 & x_{1,1} & \cdots & x_{1,j} & \cdots & x_{1,m} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 1 & x_{i,1} & \cdots & x_{i,j} & \cdots & x_{i,m} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 1 & x_{n,1} & \cdots & x_{n,j} & \cdots & x_{n,m} \end{bmatrix}, \quad \text{and} \quad y = \begin{bmatrix} y_1 \\ \vdots \\ y_i \\ \vdots \\ y_n \end{bmatrix} \tag{2}$$

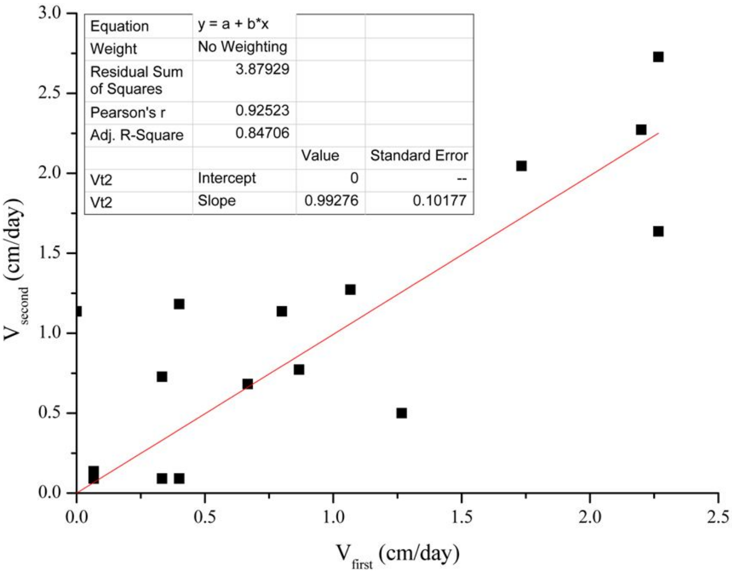

Fig. 8 The deformation rate comparison in two stages

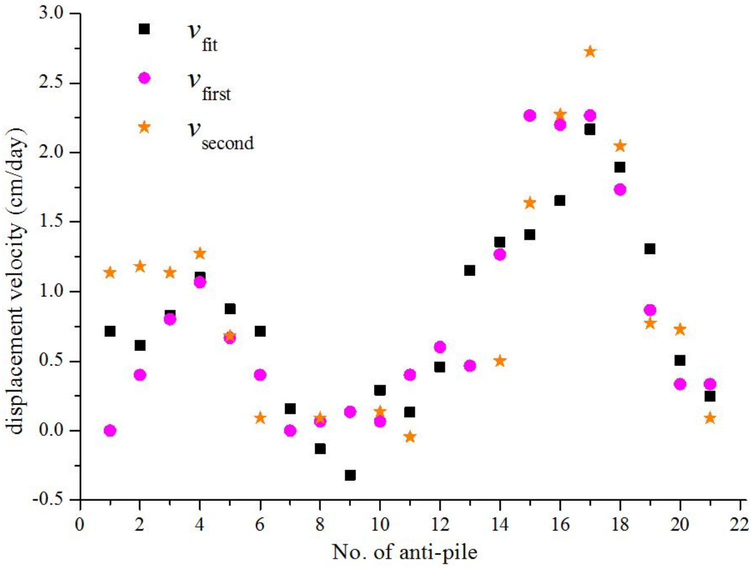

Fig. 9 Displacement velocities comparison between fit and test

Where n which represents the number of anti-piles equals to 21, and m does 6 independent factors: length of cantilever (x_1), thickness of fill (x_2), thickness of gravel soil (x_3), thickness of strongly weathered mudstone (x_4), thickness of weakly weathered mudstone (x_5) and the minimum distance of anti-pile to the two gullies (x_6). Here $x_{i,j}$ is the value of the j-th independent variables at the i-th anti-pile, y_i is the monitored average deformation rate of the i-th anti-pile. The predicted values of the dependent variable are collected in a vector denoted $\hat{y}$ and are obtained as

$$\hat{y} = Xb \quad \text{with} \quad b = (X^T X)^{-1} X^T y \tag{3}$$

where b is the column vector of correlation coefficients. $x_{i,j}$ and y_i have given in table 1, according to Eqs. (1)-(3), multiple linear regression analysis shows that $b_0 = -4.108$, $b_1 = 0.389$, $b_2 = 0.672$, $b_3 = 0.100$, $b_4 = -0.259$, $b_5 = -0.155$ and $b_6 = -0.007$.

In regression, the R^2 coefficient of determination is a statistical measure of how well the regression line approximates the real data points. Here R^2 equals to 0.901, it verifies multiple linear regression method is feasible. Fig. 9 also shows the comparison of fit velocities with the first and second stage velocities.

Correlation coefficient is a statistical indicator to reflect the related degree of the variables. The result states that the thicknesses of mudstone and the distance of anti-pile to the two gullies are negative related to the embankment stability, and the larger its value is, the better the embankment stabilizes. While the length of cantilever, the thicknesses of backfill and gravel soil are positive related and adverse to the embankment stability. The larger their values are, the worse the embankment stabilizes. The surface water has a little effect on the stability of Liujiawan fill embankment.

5. Conclusions

According to the deformation velocity, we know that the embankment is being in the stage of uniform deformation and does not reach the stage of accelerated deformation. If an effective measure would be taken to control the progressive deformation, the highway could be used normally.

(1) The field survey and monitor clarity that, all anti-slide piles deformed mainly perpendicular to the direction of highway trend without obvious bending deformation and dumping, it explains that the bottom of piles was not fixed successfully.
(2) The cantilevers of the piles mostly are too long, and there exists an 8-meter high embankment slope on the top of piles. That makes the active earth pressure behind the piles large.
(3) Multiple linear correlation analysis states that, the thickness of backfill and the cantilever length of anti-slide piles have positive correlations with the embankment displacement. The thickness of the mudstone is negative correlation with the displacement, to this embankment slope, the surface water is a fewer disadvantage in the stability of slope.
(4) Considering the six factors affecting the embankment stability, the thicknesses of anti-slide pile through the gravel, strongly weathered and slightly weathered mudstone all cannot be changed, and the distances of piles to the two gullies have been fixed too. The basic reasons of leading to the large deformations are the anchoring segment of the anti-slide pile not long enough and the cantilever part too long.
(5) From the point of changing the six factors, backfilling, which can shorten the length of pile cantilever and increase the thickness of fill earth, is the only way to improve the stability of the embankment, but the instability of the backfill will become a new trouble. Therefore other measure should be thought, for example, pre-stressed anchor cables are added on the cantilever stage of the anti-slide piles or a row of composite bolt piles are laid on its inside.

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