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The Numerical Simulation about the "Overlapping Effect of Influence Zone" of the Construction Process of Multi-stage Slope

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Abstract: The construction processes of a multi-stage slope supported by an united retaining structure of anchor-frame and anti-sliding pile were systematically studied on FLAC3D software, the influence zones of slope were drawn on CAD software. To explore the influence to the axial force of the anchor cables of the retaining structures that have been completed caused by the construction of the retaining structure by analyzing the relation between the prestress of the anchor cables and the influence zones of the multi-stage slope. The study shows that the influence zone caused by the construction will cross the influence zone of the next higher level slope if it is big enough and they will form a overlapping zone, the pretress of the anchor cable in this overlapping zone will change correspondingly, that is the "overlapping effect of influence zone" of the construction process of multi-stage slope; the area of the overlapping zone is related to the prestree applied initially, and the change of the axial force of the cables is related to the areas of the overlapping zone. This article summarizes the relationship between them, and presents the empirical formulas and provides a new method for designers in determining the ultimate pretress of the anchor cable after all the construction processes of a multi-stage slope.

Keywords: *Numerical Simulation, Multi-stage slope, overlapping zone, influence zone.*

1. Introduction

There are more and more constructions of high slop and governance issues of large-scale landslide on engineering practice, single retaining structure cannot provide sufficient stabilizing force to ensure the safe of these landslides for the huge landslide thrust, so on the projects of high slope control, engineers commonly use united retaining structure, the united retaining structure of anchor-frame and anti-sliding pile which has been used for many years is the most common form. Determining the prestress of the anchor cable is the key in the design of the united retaining structure of anchor-frame and anti-sliding pile. But the designers design the united retaining structure always base on experience or assumptions due to the lack of research design and calculation theory of the united retaining structure. If the prestrsess of the anchor cable is too huge, it will make the material wasted and improve the project cost; if the prestrsess of the anchor is insufficient will make the slope in a very dangerous condition, and threaten the security of the people all the time.

"Reserved Construction Method", which is excavation and support hierarchical, is generally used in the construction of high slope. A greater degree of safety in the construction process of a slope can be ensured through supporting immediately after excavating.(Supporting immediately after the excavation can ensure a greater degree of safety in the construction process of a slope.) Analysis theoretically, frame and anchor pile together form a dynamic force statically indeterminate system in a united retaining structure of anchor-frame and anti-sliding pile. During the construction process of each retaining structure, the initial stress state is affected by the work of prestressed anchors, meanwhile, the following construction process, the excavation of bottom slope and the work of prestressed anchors will all influence the stress state of finished structures, which is so called " Effect of construction " of multi-stage slope.

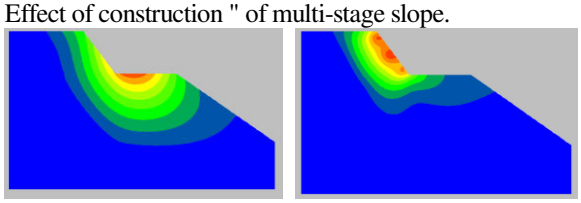


Figure 1.1&1.2 *The influence zone after third slope construction*

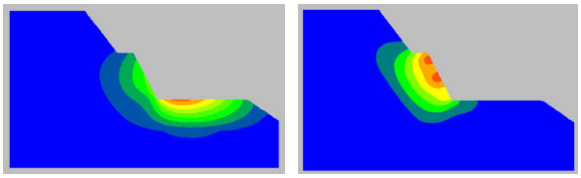


Figure.1.3&1.4 *The influence zone after secondary slope construction*

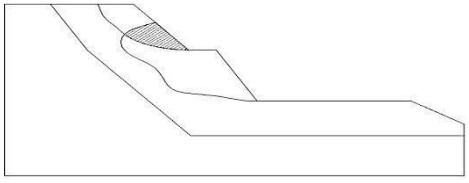


Figure 1.5 *The overlap of cable frame precompression zone of third slope and relaxation zone of secondary slope when the prestress is 100kn*

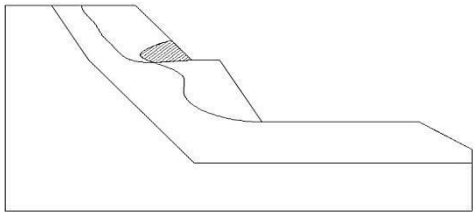


Figure 1.6 *The overlap of cable frame precompression zone of third slope and relaxation zone of secondary slope when the prestress is 1000kn*

Figure 1. *The influence zone after the construction of the multi-stage slope and the overlapping area*

The excavation of multi-level slopes can cause slope relaxation zone, and a precompression zone often follows the application of prestress in a retaining structure, which can be saw in picture 1.1,picture 1.2,picture 1.3 and picture 1.4.If the influence area due to the lower slope construction is large enough, it will overlap with the influence area caused by a former slope construction, and the overlapping zone varies as the initial prestress exerted by anchor cables varies, seeing in picture 1.5 and 1.6.The prestress of anchor cable in overlapping zone will adjust because of the construction following. This phenomenon is named as "overlapping effect of influence zone" in the construction of multi-stage slopes. "Effect of construction", which is descripted above, actually is caused by "overlapping effect of influence zone" of multi-stage slope. Because the role of "overlapping effect of influence zone", the prestress of anchor cables adjust constantly during the whole construction process. So, it is difficult to get the prestress of anchor cable, which causes a big trouble for designers in determining the prestress of anchor cable after the whole construction process.

Nowadays, there are many researches about influent zone of slopes, but there is a shortage of researches about "overlapping effect of influence zone" in our country. The software FLAC3D is applied to conduct numerical simulation researches on construction process of multi-stage slope. Combining with CAD drawing software, the influence zone of a certain level in a slope during construction process can be drawn out. Through conducting researches on "overlapping effect of influence zone" during construction process of multi-level slopes, analyzing the relationship between prestress of anchor cables and the area of overlapping influence zone, Probing the influence of construction of the following level to the finished retaining structures ,establishing the corresponding empirical formula and presenting a new calculation method to accuse the final prestress of anchorcable after the construction further, this article can be a reference to designers when they design united retaining structure of anchor-frame and anti-sliding pile.

2. The Model of numerical simulation:

2.1. Establish the model

Adopt FLAC3D software to create a three-dimensional model of the slope, as shown in Figure 2, the length of the slope is 50m, the breadth is 7m, and the height is 30m; constraints the vertical displacement in the plane of the bottom of the model, constraints the horizontal displacement in the plane at X = 0, X = 50 and Y = 0, Y = 7, and the plane at Z = 30 is free interface. The simulation of construction of multi-stage slope consists of six working conditions, the cross section and retaining structures of the Slope after the whole construction are shown in Figure 3.

Table 1. *Parameters of rock soil mass*

Slope	Bulk density /(kN/m^3)	Cohesion/kPa	Friction / (°)	Elastic Modulus /MPa
①	21.5	708	31.3	980
②	17	34.6	24.6	200

The section of the multi-stage prototype is shown as Figure 4, the bedrock is shown as Figure 4-①, the Soil of slope is shown as Figure 4-②, the soil which will be excavated is shown as ②-1,②-2 and ②-3; The slope rate of the first excavation face is 1: 0.75, The slope rate of the second excavation face is 1:0.5. Constitutive model of soil using Mohr-Coulomb elastoplastic model, the mechanics parameters of Soil is shown in Table 1; yield criterion using Mohr - Coulomb yield criterion: $f^s = \sigma_1 - \sigma_3 N_\phi + 2c\sqrt{N_\phi} = 0$, among them, $N_\phi = \frac{1+\sin\phi}{1-\sin\phi}$, c is the cohesion of soil; ϕ is the friction angle of soil. Adopt the cable and beam elements of FLAC3D software to simulation anchor framework, the material parameters of cable and frame beam (the vertical beams and horizontal beams have the same material parameters) is shown as Table 2; Adopt the cable and pile elements of FLAC3D software to simulation anchor Pile, the material parameters of anchor cable and pile is shown as Table 3, the inclination of all the cables is 26°.

Table 2. *Parameters of anchors and frame beams*

Anchor cable	Elastic Modulus (Gpa)	Cross-sectional area (m²)	Friction angle of grout (°)	Cement bond of unit length (kN/m)	Slurry stiffness of unit length (GPa)	outer circumference of grout (m)
Free period	195	5.56e-4	0	0	0	0
Anchoring period	195	5.56e-4	25	2.1e3	0.56	0.4082
Frame beam	Elastic Modulus (GPa)	Poisson's ratio	Cross-sectional area (m²)	Moment of inertia of Y (m^4)	Moment of inertia of Z (m^4)	Polar moment of inertia (m^4)
	28	0.2	0.09	6.75e-4	6.75e-4	1.35e-3

Table 3. *Parameters of anti-sliding pile*

Retaining structure	Elastic Modulus (GPa)	Poisson's ratio	Cohesion of the normal coupling spring (kN/m)	Friction angle of the normal coupling spring (°)	Spring stiffness of the normal coupling on unit length (GPa)	Cohesion of shear coupling spring (kN/m)	Friction angle of shear coupling spring (°)	Spring stiffness of shear coupling on unit length (GPa)
Anti-slide pile	30	0.2	20	25	0.9	20	25	0.9

2.2 Numerical simulation:

The numerical simulation of the whole construction uses the "Reserved Construction Method", which means we support the slope after we excavation in the same level slope. The simulation of construction of multi-stage slope consists of six working conditions: working condition 1 is the excavation of third stage slope; working condition 2 is the support of third stage slope by anchor frame; working condition 3 is the excavation of secondary stage slope; working condition 4 is the support of secondary stage slope by anchor frame; working condition 5 is the support of primary stage slope by anchor pile; working condition 6 is the excavation of primary stage slope.

In order to measure the range of the influence zone caused by construction, set four bolts with the inclination of 10°on the midline of every level slope by the simulation of injecting grout to cable element, the calculation parameters of bolt element is relatively in order to reduce the impact on the slope deformation. The main role of the bolt is the determination of the scope of the influence zone, so we can call it “Measurement Bolt”. The working principle of the “Measurement Bolt” will be shown by measuring the relaxation zone, as we can see in figure 5: setting four “Measurement Bolt” at the middle of each stage Slope, When the slope is excavated, the soil at the relaxation zone of the slope has a movement trend to slope, the soil which has the movement trend to slope will cause friction ,that point to slope, at the surface of "Measured Bolt" ,so in this zone, the axial force of “Measurement Bol” is gradually increasing . If the bolt crosse the border of relaxation zone, the friction at the surface of "Measurement Bolt" will reverse, the axial force of “Measurement Bol” will gradually decrease. Since the boundary of relaxation zone has the characteristics above, we can determine where is the boundary of the relaxation zone by judging the position where the growth trend of axial force of "Measured Bolt" sudden change. When we connect all the positions of boundary that determined by “Measurement Bolt”, we can get the relaxation zone of slope. The measurement to get the precompression zone of slope is the same, only the direction of friction at the surface of “Measurement Bolt” is on the contrary.

We can get the information of the coordinate of all the position of the boundary of the influence zone determined by “Measurement Bolt”, and then use the CAD drawing software to mark the border point, and connect them to determine the scope of each influence zone. Putting the influence zone caused by the different stage slope together, we can get the overlapping zone caused by the construction of multi-level slope, and we can obtain the overlapping zone by using the area calculation tool of CAD software, finally, we can discuss the formula of the area of the overlapping zone and the prestress of anchor cable.

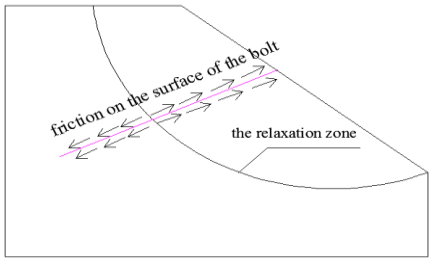


Figure 5. *The operational principle of the anchor stock for measuration*

3. The analysis of the results of simulation:

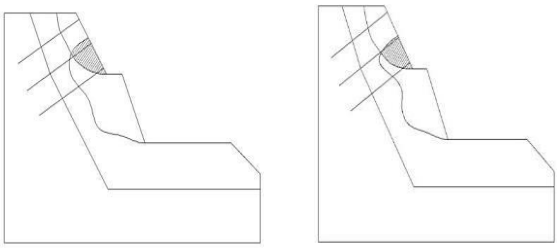
After making a series of numerical simulation about six kinds of working conditions, we can draw the influence zone of the slope of each working condition to study the relationship between the area of the influence zone and the axial force of the anchor cable, as well as the "overlapping effect of influence zone".

3.1. The "overlapping effect of influence zone" caused by the precompression zone of third slope and the excavation of secondary slope:

Making a simulation of the excavation of the second slope after the simulation of the construction of the support structure of the third level stage slope. The relaxation zone of second stages slope will be different for the different pre-stress of the supporting structure of the third level slope. If the pre-stress of the supporting structure of the third level slope is great enough, the relaxation zone of the second stage slope will cross the precompression zone of the third stage slope, the axial force of the anchor in the overlapping zone. As we can see in figure 6, 6-(a) show us the overlapping zones when the pre-stress of cable of the support structure of the third level slope is 100kN, and 6-(b) show us the overlapping zones when the pre-stress of cable of the support structure of the third level slope is 300kN, the sizes of the areas of the overlapping zone are different. Making the area of overlapping zone caused by working condition 2 and working condition 3 A_{23}, and the increment of axial force of the cable of the support structure of the third level slopeF_1, the relationship of them is shown in table 4, ΔF_{23} mean the changes of the axial force of the cable of the support structure of the third level slope from condition 2 to condition 3.

What can we learn from table 4 are that the axial force of the anchor cables in the crest of third stage slope

has no changed, and the axial force of the cables in the waist and foot of the third stage slope have different degrees of increase, this is because the anchor cables in crest are not in the overlapping zone, but the anchor cables in the waist and foot are in the overlapping zone, the overlapping zone will lose the soil of third stage slope and stretch the cable in overlapping zone; besides, the area of overlapping zone in the foot is much larger than that in the waist, so the increment of the axial force of the cables in the foot are much larger than that in the waist, this is one of the "overlapping effect of influence zone". Moreover, A_{23} will decrease as the F_1 is increased, makeF_1 as independent variable and A_{23} as dependent variable, we can obtain the empirical formula between F_1 and A_{23};make A_{23} as independent variable and ΔF_{23} as dependent variable, we can obtain the empirical formula between ΔF_{23} and A_{23}, the results are shown in table 5.



(a)F_1=100kN *(b)F_1=300kN*

Figure 6. *The overlap of cable frame precompression zone of third slope and relaxation* zone of secondary slope

Table 4. *Relationship between pre-stress and overlapping area and axial force increment*

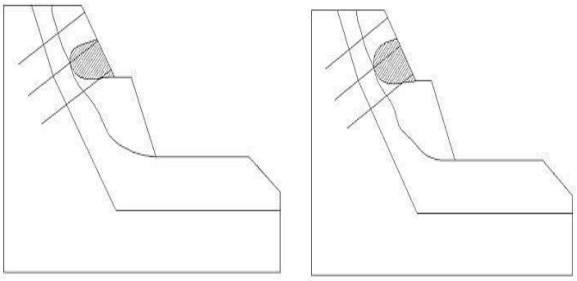
prestressF_1/kN		100	200	300	400	500	800	1000
The area of overlapping zone A_{23}/m^2		16.46	15.13	13.94	13.05	12.92	12.03	10.79
Axial force increment of third slope /N	slope crest	0	0	0	0	0	0	0
	Slope Waist	1140	1100	1000	900	800	670	500
	slope Foot	4550	4300	4100	3900	3700	3200	2600

Table 5. *Empirical formula about A_{23}-F_1 and ΔF_{23}-A_{23}*

Category		Empirical formula	Correlation coefficient R^2
A_{23}-F_1		$A_{23} = 27.435 - 2.36 \ln F_1$	0.9819
ΔF_{23}-A_{23}	Slope Waist	$\Delta F_{23} = \frac{1295 + 0.8754A_{23}}{1 + e^{-0.4882(A_{23}-12.4891)}}$	0.9658
	slope Foot	$\Delta F_{23} = \frac{4530 + 3.9942A_{23}}{1 + e^{-0.6182(A_{23}-10.4938)}}$	0.9624

3.2 The "overlapping effect of influence zone" caused by the precompression zone of third and secondary stage slope:

Numerical simulation is carried out on the working condition of 4, the precompression zone of second stage slope is different also when the pre-sress (F_2) of the cable of the retaining structure of second level slop is different. The precompression zone of second slope will cross the precompression zone of third level slope when it is big enough, the anchor axial force in this overlapping zone will change. Figure 7-(a) show us the overlapping zones when the pre-stress of cable of the support structure of third level slope is 800kN and the pre-stress of cable of the support structure of second level slope is 500kN, Figure 7-(b) show us the overlapping zones when the pre-stress of cable of the support structure of third level slope is 800kN and the pre-stress of cable of the support structure of second level slope is 1000kN, the area of overlapping zone A_{24}, prestress of cable F_2, the axial forces increment ΔF_{34} ans their relationship are shown as table 6. A_{24} means the area of the overlapping zone caused by condition 2 and condition 4, also means the area of the precompression zone of second slope cross the precompression zone of third level slope, F_2 means the axial forces of cables of the retaining structure of second stage slope, ΔF_{34} means the change of axial force of cable in second level slope from condition 3 to condition 4.



(a)F_2=500kN *(b)F_2=1000kN*

Figure 7. *The overlap of cable frame precompression zone of third slope and secondary slope*

What can be seen from the table 6 are that A_{24} increases with the increase of F_2, absolute value of ΔF_{34} increases with the increase of A_{24}, the axial force of the cables in the crest of third stage slope have no change, and the increment of the axial force of the cables in the waist and foot of third stage slope is negative. Why the axial force of the cable in the waist and foot of the third stage slope decrease is because these cables are in the overlapping zone of two precompression zone, the overlapping zone can lose the soil in third stage slope, the deformation of these cables will decrease, which result in the decrease of the axial force of the cable in the waist and foot of the third stage slope. The cables in the crest of the third stage slope are not in this overlapping zone, so their axial force has no change. This is another "overlapping effect of

influence zone". The relationship and formula between F_2 and A_{24}, ΔF_{34} and A_{24} are shown in table 7.

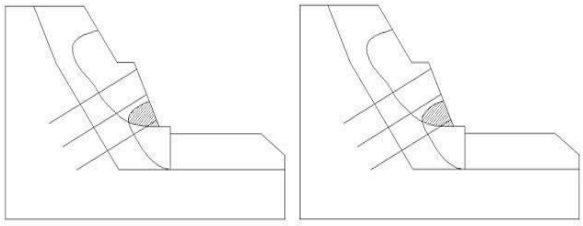
Table 6. *Relationship between pre-stress and overlapping area and axial force increment*

prestressF_2/kN		100	200	300	400	500	800	1000
The area of overlapping zoneA_{24}/m^2		14.4	16.5	18.66	21.78	23.17	25.63	27
Axial force increment of the third slope ΔF_{34}/N	slope crest	0	0	0	0	0	0	0
	Slope Waist	-170	-270	-420	-670	-790	-1270	-1570
	slope Foot	-1000	-1500	-2150	-3350	-4150	-6200	-7800

Table 7. *Empirical formula about A_{24}-F_2 and ΔF_{34}-A_{24}*

Category		Empirical formula	Correlation coefficient R^2
A_{24}-F_2		$A_{24} = 3.72705F_2^{0.28872}$	0.97894
ΔF_{34}-A_{24}	Slope Waist	$\Delta F_{34} = 44.59704 + 27.03548\left(1 - e^{A_{24}/6.57819}\right)$	0.97708
	slope Foot	$\Delta F_{34} = 128.12878 + 156.99224\left(1 - e^{A_{24}/6.85308}\right)$	0.98033

3.3. The "overlapping effect of influence zone" caused by the precompression zone of the secondary and primary stage slope:



(a)F_3=500kN *(b)F_3=1000kN*

Figure 8. *The overlap of cable frame precompression zone of secondary slope and cable pile precompression zone of primary slope*

In order to study the overlapping zone between the precompression zone of the secondary stage slope and the precompression zone of primary stage slope, the numerical simulation of the construction of the primary stage slope is carried out after the accomplishment of the numerical simulation of the construction of the secondary stage slope with the prestress of the anchor cable of the retaining structure is 800kN. Figure 8-(a) show us the overlapping zone when the prestress of anchor cable of the retaining structure of secondary level slope is 800kN and the prestress of anchor cable of the retaining structure of primary level slope is 500kN, Figure 8-(b) show us the overlapping zone when the prestress of anchor cable of the retaining structure of secondary level slope is 800kN and the prestress of anchor cable of the retaining structure of primary level slope is 1000kN,take F_3 as the prestress of the anchor cables primary level slope, A_{45} as the areas of the overlapping zone caused by condition 4 and condition 5, ΔF_{45} as the change of the axial force of the anchor cables in secondary stage slope from condition 4 to condition 5 .The axial force of the anchor cable in the crest and waist of the secondary stage slope have no change for they are not in overlapping zones, and the axial force of the anchor cables in the foot decreases for it cross the overlapping zones. The relationship and empirical formula between A_{45} and, F_3, ΔF_{45} andA_{45} are shown in table 9.

Table 8. *Relationship between pre-stress and overlapping area and axial force increment*

prestressF_3/kN		100	200	300	400	500	800	1000
The area of overlapping zone A_{45}/m^2		9.956	10.71	11.68	12.29	12.57	12.85	13
Axial force increment of the secondary slope ΔF_{45}/N	slope crest	0	0	0	0	0	0	0
	Slope Waist	0	0	0	0	0	0	0
	slope Foot	-200	-226.1	-366.2	-662	-942.7	-1359.3	-1700.2

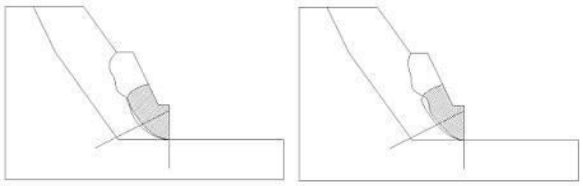
Table 9. *Empirical formula about A_{45}-F_3 and ΔF_{45}-A_{45}*

Category		Empirical formula	Correlation coefficient R^2
A_{45}-F_3		$A_{45} = 5.71396F_3^{0.1228}$	0.95998
ΔF_{45}-A_{45}	Foot of secondary slope	$\Delta F_{45} = -189.07864 + 1.1 \times 10^{-6}\left(1 - e^{A_{45}/0.61808}\right)$	0.97152

3.4. The "overlapping effect of influence zone" after primary slope excavation:

The Numerical simulation of working condition 6 ,that is the construction of the excavation of primary stage slope after the model of slope calculating balance under different prestress of the retaining structure of primary stage slope , stage slope A_{56}, and the Numerical simulation of working condition 6 ,that is the construction of the excavation of primary stage slope after the model of slope calculating balance under different prestress of

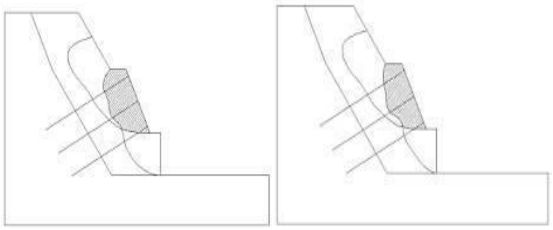
the retaining structure of primary stage slope ,is carried out. We can get the information about the area of the overlapping zones of the relaxation zone of primary stage slope and the precompression zones of primary stage slopeA_{56}, and the overlapping zone of the relaxation zone of the first stage slope and the precompression zone of secondary slope, A_{46},as well as the change of the axial force of all the cables under the effect of the construction of the excavation of primary slope, and they are shown in table 10. The empirical formulas of ΔF_{56} and A_{46} are shown in table 11.



(a)F_3=100kN *(b)F_3=300kN*

Figure 10. *The overlap of relaxation zone and cable pile precompression zone of primary slope*

The calculation formulas in table 11 essentially meet the boundary conditions that when A_{46}=0 then ΔF_{56}=0, and when A_{56}=0 then ΔF_{56}=0 . There is a big increase in the axial force of the anchor cables in the primary stage and second stage slope after the construction of the excavation of primary stage slope, at the same time, the axial force of the anchor cables in third stage slope only have a little bit change for the relaxation zone of the primary stage slope do not cross the precompression zone of the third stage slope but cross the precompression zone of primary and secondary stage slope. The shaded parts as we can see in figure 9 respectively are the overlapping zones of the relaxation zone of the primary stage slope and the precompression zone of the secondary stage slope when F_3=100kN and F_3=300kN.The shaded parts as we can see in figure 10 respectively are the overlapping zones of the relaxation zone of the primary stage slope and the precompression zone of the primary stage slope under F_3=100kN and F_3=300kN.The construction of the excavation of primary stage slope will lose the soil of the solpe and have a "Weakening" effect on the retaining structure that have been constructed, which will slack the anchor cable and increase the axial force of the anchor cables, On the other hand, it also illustrates that the anti-slide pile and the anchor-frame Share the landslide thrust and from a kind of united retaining structure of anchor-frame and anti-sliding pile. The axial force of the anchor cables in the primary stage slope have a bigger change than that in the secondary level slope, because the deformation of the surrounding rock and soil in primary slope is more large which cause the landslide thrust is bigger. It also illustrates that the anti-sliding pile share more of the landslide thrust than the anchor-frame. That is the "affected zone overlapping effect" after the excavation of the first level slope.



(a)F_3=100kN (b)F_3=300kN

Figure 9. *The overlap of relaxation zone of primary slope and cable frame precompression zone of secondary slope*

Table 10. *The area of influence zone and axial force increment after primary slope excavation*

prestressF_3/kN			100	200	300	400	500	800	1000
The area of overlapping zone A_{56}/m^2			38.919	37.876	37.08	36.495	35.524	34.489	32.956
The area of overlapping zone A_{46}/m^2			47.28	44.36	41.44	29.64	27.312	25.419	23.913
Axial force increment after primary slope excavation ΔF_{56}/N	Third slope	slope crest	100	100	100	100	0	0	0
		Slope Waist	200	200	200	100	100	100	100
		slope Foot	300	200	200	200	100	100	100
	Secondary slope	slope crest	1050	980	900	690	560	470	400
		Slope Waist	1500	1400	1330	1000	880	700	600
		slope Foot	4050	3900	3800	3400	3250	3000	2800
Primary slope				16200	13400	11500	9900	6400	4400

Table 11. *Empirical formula aboutΔF_{56}-A_{46} and ΔF_{56}-A_{56}*

Category			Empirical formula	Correlation coefficient R^2
ΔF_{56}-A_{46}	The anchor cable of secondary slope	slope crest	$\Delta F_{56} = \frac{900 + 3.7763A_{46}}{1 + e^{-0.17912(A_{46}-26.43281)}}$	0.96028
		Waist of the Slope	$\Delta F_{56} = \frac{1050 + 10.15618A_{46}}{1 + e^{-0.19899(A_{46}-24.86816)}}$	0.95937
		Foot of the slope	$\Delta F_{56} = \frac{1870 + 47.9582A_{46}}{1 + e^{-0.39128(A_{46}-16.21053)}}$	0.96701
ΔF_{56}-A_{56}	The anchor cable of anti-sliding pile		$\Delta F_{56} = 0.00000000003459 89A_{56}^{9.2865} + 10.01013A_{56}$	0.98999

4. Conclusions:

(1) The influence zones caused by construction of the multistage slope will overlap each other and form an overlapping zone. The different prestress initial of the anchor cable will cause various influence zone of the slope. If the influence zone caused by the construction is

large enough, it will cross the influence zone caused by the previous construction and form an overlapping zone.

(2) When the relaxation zone overlap with the precompression zone caused by the previous construction, the soil in this overlapping zone will be loose and the axial force of the anchor cable will increase. The axial force of the anchor will increase more when the area of the overlapping zone is larger, and will has no change when it is not in the overlapping zone, we call this "overlapping effect of influence zone".

(3) When the precompression zone overlap with the precompression zone caused by the previous construction the soil in this overlapping zone will be compacted and the axial force of the anchor cable will decrease, we call this another "overlapping effect of influence zone". Actually, "overlapping effect of influence zone" is the root cause of the anchor cable prestress changes.

(4) The area of the overlapping zone is related to the prestress applying initial of the anchor cable, the change of the axial force of the anchor cable is related to the area of the overlapping zone. This article summarizes the relationship between them and presents the empirical formula, which can provide the designer a new way to determine the axial force of the anchor cable after all the constructions of the multi-stage slope.

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