Stability evaluation and treatment of a deformable rockmass in the Three Gorge Reservoir Area, China

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Abstract: The stability evaluation and control design of a deformable rockmass body was one of the most challenging problems encountered during the construction of the Three Gorge Reservoir in China. Part of the rockmass body appeared to be deforming where as the whole rockmass remained stable. The evaluation and improvement of the stability of a landslide appeared to be different for each location. This paper will aim to introduce the research methodology followed in order to control the design on a deformable body. Three key factors were identified and are introduced below:

- The determination of the most dangerous sliding surface: for the consequent bankslope, it should be decided according to the rear edge deformation and the bedding plane; as for the not consequent bankslope, it should be confirmed considering the preponderant joint combination angle, the tensile cracks, FSK method and the structural plane network simulation results.
- The arrangement of reasonable position of the anti-slide piles: when the deformation is serious, the piles should be placed in the descendant section of the pushing force diagram and above 175m water level; when it isn't, they should be placed in the rear part of the deformable body where there is no deformation.
- The determination of the design pushing force: not considering the resistance of the rock and soil mass before the piles, it is the maximum value under different conditions; concerning resistance, it can be the maximum value at the shearing-out point under different conditions or the difference between the maximum value of the design and checkout condition and value under natural condition.

To summarise taking the example of the Archives Office deformable body, which lies in the Three Gorge reservoir area, with the above method, first the sliding surface is determined, then the stability is evaluated with the residual pushing force method, and the positions of the piles and design pushing force are decided.

Résumé: L'évaluation de la stabilité et le projet de l'aménagement du corps de la roche déformée est un des problèmes importants durant la construction du Réservoir Trois Gorges. Comme le corps déformé est le corps de la roche en train d'être déformé mais pas détruit totalement, la façon de son évaluation de la stabilité et le projet de son aménagement sont différents de ceux concernant les calamités des glissements de terrain. Et les problèmes cruciaux des deux ne sont pas pareils non plus. Tenant compte des caractéristiques du corps déformé, ce texte donne une façon de recherche sur les étapes de l'enquête géologique, de l'étude de la stabilité et du projet de l'aménagement. Les trois problèmes cruciaux sont la détermination de la face la plus dangereuse de glissement total, celle des positions raisonnables des pieux anti-glissements et celle de la poussée de projet.

- La détermination de la face la plus dangereuse de glissement total doit être considérée selon deux conditions : ① pour la pente de rive conséquente, il faut déterminer la face de glissement total selon la situation de déformation du bord d'arrière et la couche de la rive. ② pour la pente de rive non-conséquente, il faut d'abord étudier la structure de la roche de la rive et la condition des couches, et puis étudier de l'angle combinatoire des différentes faces structurales prépondérantes, et déterminer la face la plus dangereuse selon la condition du craquement du bord d'arrière et en vertu du résultat de la simulation du réseau des faces structurales et les données de l'enquête géologique, en utilisant la méthode FSK.
-La détermination des positions raisonnables des pieux anti-glissements doit être considérée selon deux conditions : ① quand la déformation est grave, il faut déterminer les positions des pieux selon la méthode du glissement de terrain, c'est-à-dire, les pieux doivent se situer à la section descendante de la courbe de poussée, la section d'anti-glissement de la pente, et au dessus du niveau d'eau :175m; ② quand la déformation du bord d'arrière est évidente, mais le bord d'avant est stable, il faut situer les pieux à la part non-déformée à l'arrière du corps.
-La détermination de la poussée doit être considérée selon deux conditions : ①quand on ne considère pas la force de résistance d'avant, et le corps de roche n'offre pas de force de résistance, à cause de l'excavation et de l'érosion du fleuve, la poussée du projet doit adopter la poussée maximum aux positions des pieux aux différentes conditions de travaux ; ② quand on considère la force de résistance du corps de roche devant les pieux : adopter la poussée maximum du shearing-out point aux différentes conditions de travaux comme la poussée P1 ; adopter l'écart entre la poussée maximum de la condition du projet ainsi que de la vérification et celle de la condition naturelle comme la poussée P2.

En résumé, on prend comme exemple le corps déformé du Bureau d'archives de Gaoyang, Xingshan qui se situe dans la zone du réservoir Trois Gorges. En vertu de cette façon de recherche proposée, et sur la base des données de l'enquête géologique, on détermine la face de glissement total, et évalue la stabilité par la méthode de poussée excédante. Et en considérant la condition concrète du corps déformé, on détermine les positions des pieux anti-glissements et la poussée de projet pour faire le plan des travaux de l'aménagement anti-glissement.

Mots-clés : le corps déformé de rive de réservoir, la face la plus dangereuse de glissement, les positions raisonnables de pieux anti-glissement, la poussée de projet, le plan d'installation des pieux anti-glissements.

Keywords: Slope stability, landslide, deformation, design, piles, reservior

THE RESEARCH METHOD OF THE RESERVOIR BANK DEFORMABLE BODY

At present, the stability evaluation and control design of deformable rock mass body is one of the most important problems encountered during the Three Gorge Reservoir construction (Tang Hui-Ming, 2003). Because the deformable body is the rock and soil mass that is deforming but has no integral failure, its stability evaluation and treatment method is different from the general landslide hazards. According to the character of the deformable body, the research sequence that is from geology investigation, stability evaluation to control design was proposed, which is showed in Figure 1. Among these, there are three key problems which are pointed as following: the determination of the most dangerous sliding surface, the arrangement of reasonable position of anti-slide piles and the determination of the design pushing force.

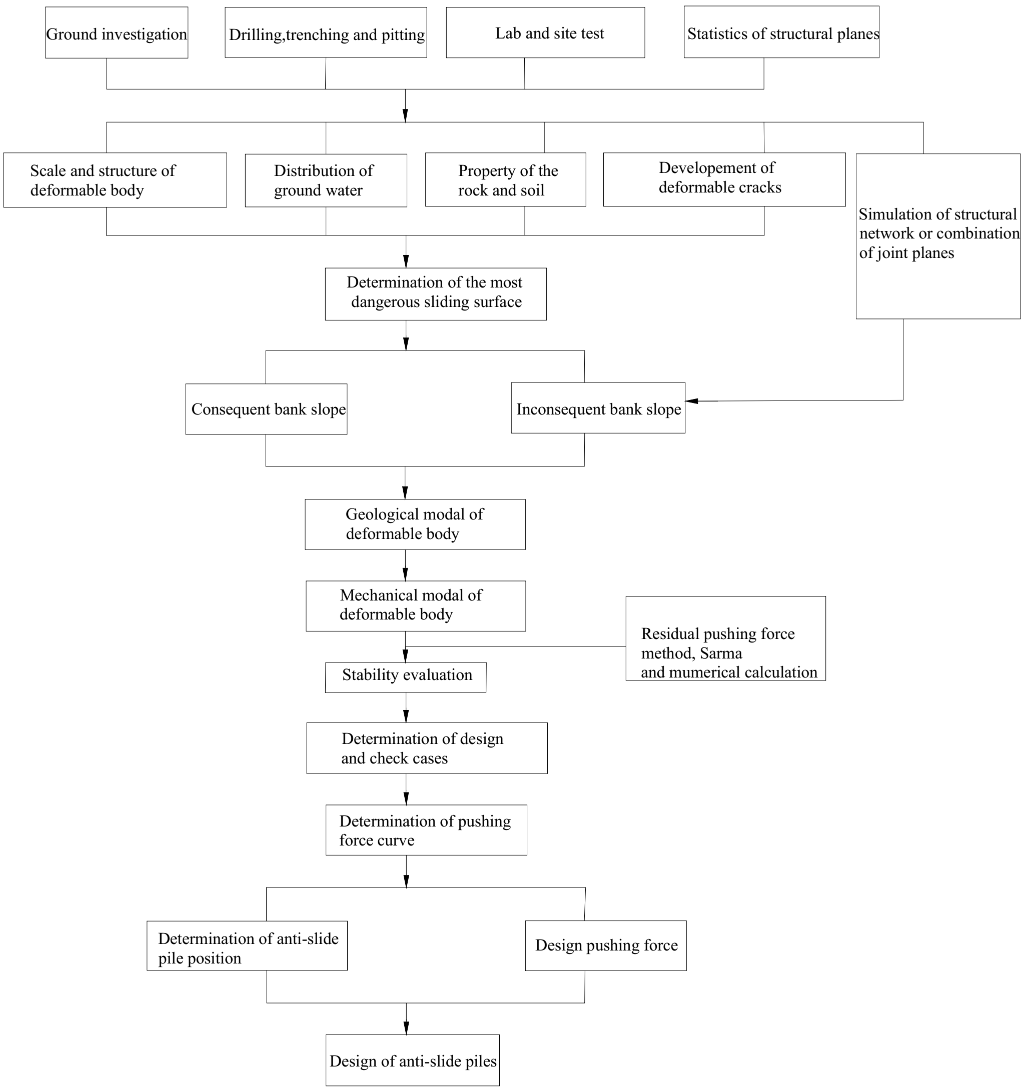


Figure 1. The research sequence of the stability evaluation and treatment of the reservoir bank.

THE DISCUSSION OF KEY PROBLEMS

The determination of the most dangerous sliding surface

The establishment of the deformable body of the reservoir bank mainly depends on the determination of the most dangerous sliding surface. The determination can be divided into two aspects: (1) For the consequent bank slope, the whole sliding surface should be decided according to the rear edge deformation and the bedding plane; (2) For the inconsequent bank slope, it should be confirmed considering the preponderant joints combinatorial angle, the tensile cracks, FSK method and the structural plane network simulation results. Firstly the rock mass joint and the layer attitude are measured. Then on the base of measured results, the preponderant joints combinatorial angle is determined. And according to the extent of the tensile cracks, combining FSK method based on limiting equilibrium method, structural plane network simulation results and the preponderant joints combinatorial angle, the most dangerous sliding surface can be confirmed. The detailed method is listed as following:

① According to the practical survey data, the rear edge point of the most dangerous sliding surface was determined;
② Limit equilibrium height(H90) can be conformed by FSK(Russia ХесеНКОВ) method, that is:

$$H_{90} = \frac{2c}{\rho}\tan\left(45° + \frac{\varphi}{2}\right)$$

where: ρ –density; c, φ – are cohesion and angle of internal friction;
③ From the top to the downwards, using FSK graphing method, incidence is $45° + \varphi / 2$;
④ Continue to the downwards, the sliding plane was determined according to considering the preponderant joints combinatorial angle;
⑤ The lowest point-the angle of the shearing-out point is determined by FSK construction method , incidence is $45° - \varphi / 2$.

The arrangement of reasonable position of anti-slide piles and the determination of design pushing force

The arrangement of reasonable position of anti-slide piles should also divided into two aspects: ①when the deformation is serious, the piles should be lied in the descendent part of the pushing force figure, that is the resistant part of the landslide, and they should be lied in above 175m reservoir water level; ②when the deformation in the after part is not serious, and the front part is stable, the piles should be lied in the back part of the deformable body.

The decision of optimisation design pushing force can also divided into two aspects (Anon, 1983; Daizihang, 2002; Hu et al, 2001; Huang et al, 1994; Springman, 1989; Zhang et al, 2002; Zheng et al, 1998,):

no considering resistance of the rock and soil mass before the piles:

When the rock and soil mass have no resistance due to the excavation and erosion of the river, the maximal value of the pushing force under different cases should be the design pushing force;

concerning resistance before the piles:

At present, there are three common methods to determine the design pushing force:

One method is directly using the shearing-out point pushing force as design pushing force P1;

The second one is using the difference between the maximal value of the design case and the checkout case and the pushing force under normal water level as design pushing force P2;

The third one is using the maximal value of P1 and P2 as the design pushing force.

The three methods mentioned above are all not perfect: the determination of P1 is lack of mechanical support; the determination of P2 is lower than the real value, because its concerning the resistance before the pile.

Hence, the method should be determined as following: The AB part can be calculated according to the normal pushing force calculation formula, and the pushing force can be calculated under the natural case, design case and the checkout case. In addition, the pushing force curve can be drawn, too. The BC part begins from the last item block and its pushing force is 0, so Fn=0. The pushing force of the item blocks between C and B part can be calculated according to the formula 1 as following. The pushing force curve can be drawn as well.

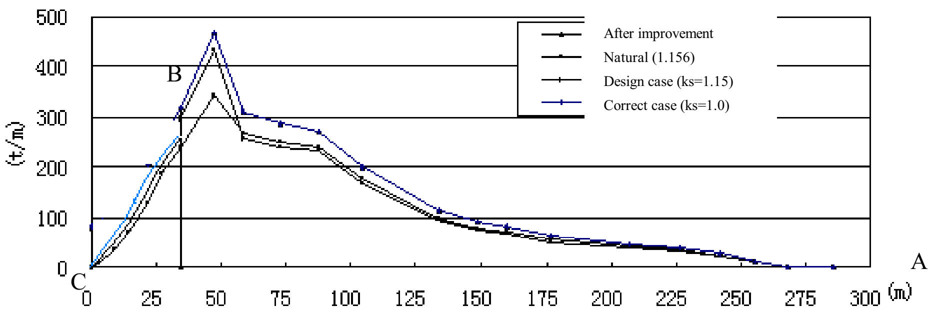


Figure 2. The analysis chart of design push force.

$$F_{i-1} = \{F_i - (W_i \sin\alpha_i + Q_i \cos\alpha_i) - [c_i L_i + (W_i \cos\alpha_i - Q_i \sin\alpha_i) f_i] / K_s\} / \psi_{i-1} \qquad (1)$$

where:

Fi is the pushing force of i item (kN/m);
Wi is the unit weight of i item (kN/m);
αi is the sliding bottom surface slope angle of i item;

Qi is the horizontal force of I item;
Ks is anti-slide safety factor, using 1.15;
ci is the sliding bottom surface cohesion of I item;
Li is the sliding bottom surface length of I item;
Fi-1 is the pushing force of I-1 item (kN/m);
Fi is the sliding bottom surface friction factor of I item;
ϕi is the internal friction angle of I item(º);
αi-1 is the sliding bottom surface slope angle of I-1 item;
ψi-1 is the transfer coefficient, which can be calculated as following:

$$\psi_{i-1} = \cos(\alpha_{i-1} - \alpha_i) - f_i \sin(\alpha_{i-1} - \alpha_i) / K_s$$

The D-value of the B point between AB part and BC part can be calculated under different cases, and the largest one is determined as the design value. Because part of the pushing force needs to transfer downward, the design value should be larger than the calculated value, that is:

$$P = P' / (1 - \xi)$$

where: ξ is the transfer coefficient of pushing force, 0<ξ<1, which is determined by experience or experience analogy method (Figure 2).

EXAMPLE

Archives Bureau deformable body (Figure 3) is located on the back hill slope of the county committee, the left bank of the Xiangxi River. The altitude of the fore part is about 170m, and the width is about 110m; the altitude of the aft part is about 230.8m, and the width is about 80m. The direction of the axis is 190°, and the longitudinal length is 100~165m. The area is $1.75\times10^4 m^2$, and the volume is about $19.6\times10^4 m^3$. The fore part and the south of the Archives Bureau comprise a steep slope, grading between 30~40°; the aft part and the north of the Archives Bureau forms an "echelon" gentle slope. Based on the borehole information and the excavation of the shallow exploratory shaft, the thickness of the deformable body is 13m, and the thickness of the slope wash (including alluvium clay, shiver and gravel) is 0.3~5m; the middle and underneath is 13m thickness fractured and loose rock. Though the ground keeps a certain layer sequence, there are fractured and loose parts and the layer attitude is 30~40° ∠20~50°.The underlying bedrock of the deformable body is Niejiashan Group mud stone and thin, medium-bedded sandstone and siltstone. The orientation and dip of the rock layer is 208° ∠70°, which is reverse to the upper part, so there is an obvious bending tilting phenomenon. There are two east-west directions, curved, 10~30m in length, 2cm in width cracks in the side of the road, which is behind the county committee dormitory building in the aft part of the deformable body. One the floor in the south of the dormitory building there is about 50m long, nearly east-west direction cracks. In the steep and gentle slope connection parts of the middle sections, there are several 55cm in length, 10cm in width, nearly east-west strike tensile cracks. The deformable body is the high incidence soft rock slope long-term creep result under the dead load stress field. The rainstorm (or long-term rain), the influent of the domestic water and the loading of the building in the aft part are the predisposing causes of its deformation.

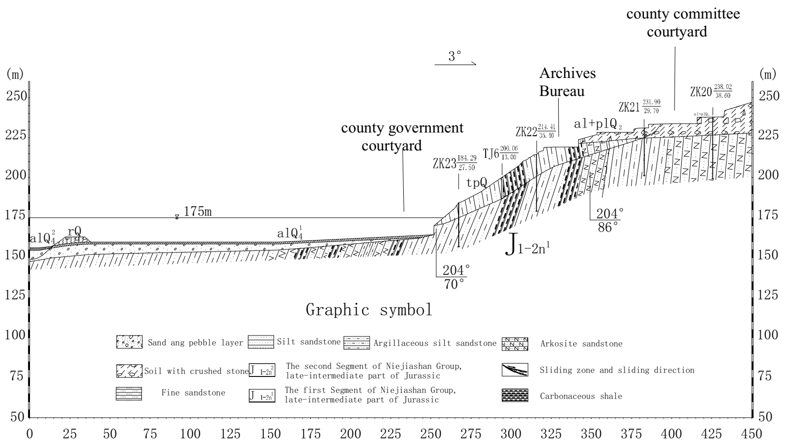


Figure 3. The geological section of the Archives Bureau deformable body.

Stability analysis

All cases after the reservoir impounding that may occur should be considered, especially the most dangerous case. The calculated scheme can be determined as following:
case 1: natural case;
case 2: natural case + rainstorm;

case 3: 175m water level + rainstorm;
case 4: 175m water level falling to 155m water level;
case 5: 175m water level +rainstorm+ earthquake(intensity: VI degree)

The position of the most dangerous sliding surface can be determined according to the site structural plane and ground cracks.

According to the test results, parameter inversion and parameter analogy, the calculation parameters of rock deformable body can be determined as following: the internal friction angle of latent sliding zone under natural and saturated state are separately 28° and 22°; the cohesion of latent sliding zone under natural and saturated state are separately 23 kPa and 20 kPa; the unit weight of slide mass under natural and saturated state are separately 24.5 kN/m3 and 2.65 kN/m3; the cohesion of slide mass under natural and saturated state are separately 50kPa and 40kPa.

The calculated results show that: the safety factor of the deformable body under natural state is 1.07, and it is in a stable state on the whole, but the safety reserve is low. The safety factor of Archives Bureau deformable body under case 2 is 1.02, and it is the limiting equilibrium state. The safety factor of deformable body under case 3 (175m water level and rainstorm) is 1.0, and it is the limiting equilibrium state. The safety factor of deformable body under case 4 (175m water level falling to 155m water level) is 0.82, and it is not stable. The safety factor of deformable body under case 5 (175m water level, rainstorm and earthquake) is 0.70, and it is not stable.

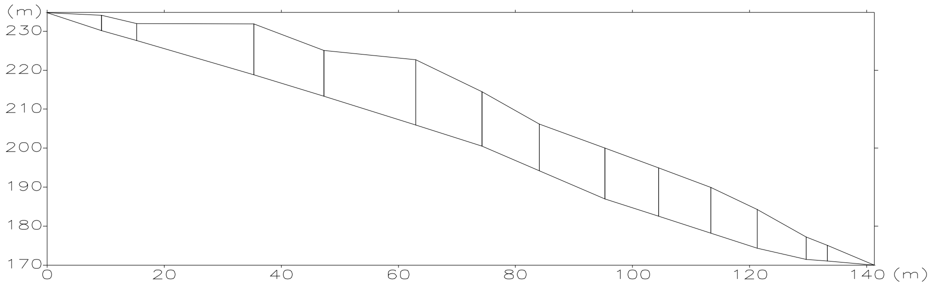
Anti-slide pile design

Pushing force calculation

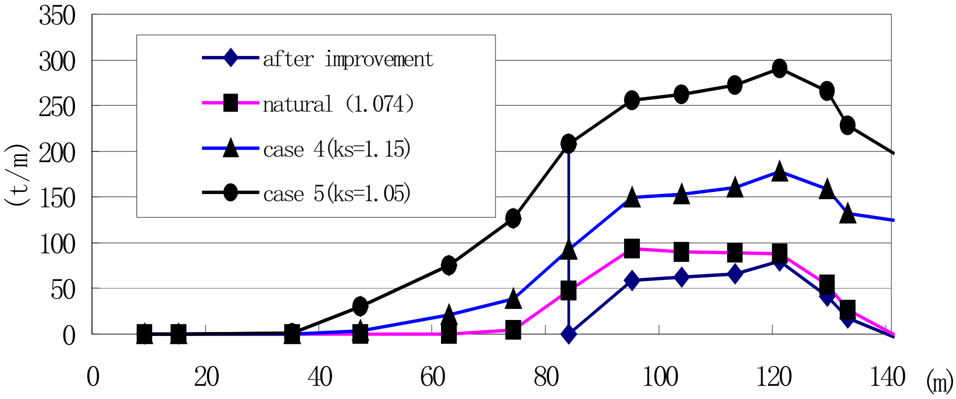
Based on the character of the Archives Bureau deformable body, the representation section chosen are calculated and its mesh subdivision figure are shown in Figure 4. Using the transfer coefficient method. The pushing force curve is shown in Figure 4. Because there is serious deformation in the aft part of the Archives Bureau deformable body, the pile position should be arranged in the aft part of the deformable body. The pushing force in the pile position is 210t/m.

Anti-slide pile design

The anti-slide piles are designed as the bending resistance component. The altitude of the pile-top in the main section is 207m. There are 15 piles in total. The number of the 8A(20m) type pile is 11, and the number of the 8B(15m) type pile is 4. The moment and shearing force figures of the 8A type are shown in Figure5.



(a)The section mesh subdivision of Archives Bureau deformable body



(b)The pushing force curve of the Archives Bureau deformable body

Figure 4. The section mesh subdivision and pushing force curve of the Archives Bureau deformable body.

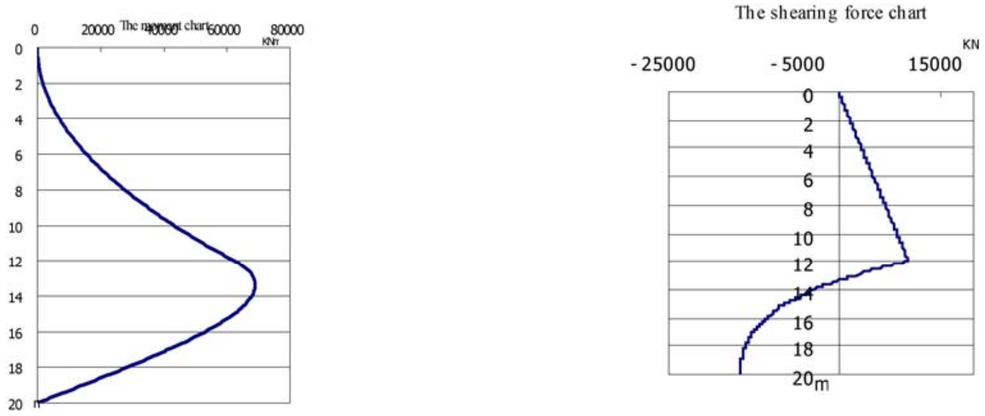


Figure 5. The moment and shearing force chart of the 8A type pile in Archives Bureau deformable body

8A type pile : length h is 20m•there into the load-bearing part h1 is 12m, anchoring length h2 is 8m. 8B type pile : length h is 15m•there into the load-bearing part h1 is 9m, anchoring length h2 is 6m. The deformation coefficient of 8A type and 8B type are all 0.191. The calculation depth of 8A type satisfies: h2=1.529>1.0, The calculation depth of 8B type satisfies: h2=1.146>1.0. Hence, the two types piles are all calculated with the method of elasticity pile. The boundary condition of the piles are hinged support. The terrane attitude checkout coefficient K1 is 0.5, and the discount coefficient of rock crack and weathering C is 0.3, and the uniaxial compressive strength R(or c) is 35Mpa. As for 8A type pile: K1×C×R=5250kPa> max=2246.47kPa; As for 8B type pile:K1×C×R=5250kPa> max=2506kPa. Therefore, the anchoring length satisfies the depth need.

The distributed steel structure figures are shown in Figure 6 in detail.

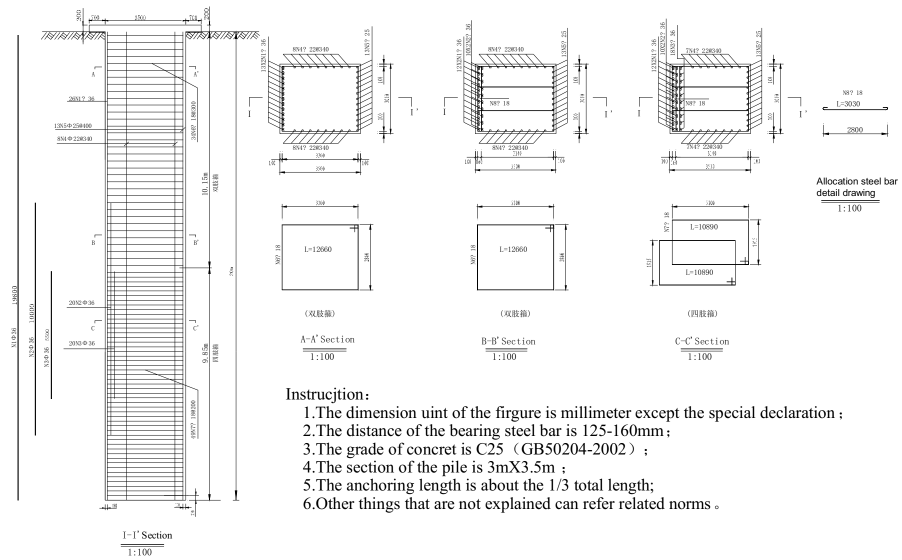


Figure 6. The structure figure of A type anti-slide pile in Archives Bureau deformable body.

CONCLUSION

As for the prominent problems: the stability evaluation and•the improvement of the deformable body in the reservoir bank in the Three Gorges Reservoir Area, the research sequence from geology investigation, stability evaluation and control design was proposed. The determination method of the three most key problems: the determination of the most dangerous integral sliding surface, the rational position of anti-slide pile and the determination design pushing force, are given, which can be as reference and instance in deformable body treatment of the three-stage geological hazard task.

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