Investigation of a landslide in the new site of Badong County by integrated geophysical survey

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Abstract An integrated geophysical survey which combines vertical seismic profile method, shallow reflection seismic method, electric sounding, soil temperature measurement and radioactive gas measurement was used to investigate Zhaoshuling landslide in the new site of Badong County and to assess the stability of the landslide. By rational use of these methods together with borehole geological profile and other geological information, the spatial distribution of the landslide body, the formations and structures within and without the landslide body were determined and the stability of the landslide was also assessed, thus making great contribution to the successful and rational investigation and assessment of the landslide.

Keywords: landslide, investigation of a new site, stability assessment, integrated geophysical survey, vertical seismic profile.

The well-known Three-Gorge Project has started. The Badong County located on the southern bank of Yangtze River is to be moved to a new site. Therefore investigation of the new site is an important task. During the investigation, however, in the centrical part of it, a landslide named Zhaoshuling landslide was discovered. Consequently, a correct assessment of the stability of the landslide is of great importance. Therefore, in this area, a detailed geological engineering survey which used traditional techniques, including drilling, trenching and tunneling, was carried out by the Engineering Geological Party which is responsible for the investigation of the new site to investigate the formation and structures in the landslide slope and its water saturation, as well as the properties and status of the soil and rocks comprising the slope. Owing to certain limitations of these techniques, however, it was still difficult to investigate and assess all these problems satisfactorily and economically, and a reasonable assessment of the landslide could not be finally made. Therefore, an integrated geophysical survey was conducted to improve and to speed up the investigation and assessment.

1 Geological setting

The area studied is located on the southern bank of the Yangtze River, 6 km west of Badong County. The area is made up of Middle Triassic rocks and Quaternary deposits, as is shown in the geological map of the area (fig. 1).

The Middle Triassic rocks are mainly composed of the second and third members of Badong group, which is named by F.V. Richthofen and is equivalent to Anisian. It is subdivided into four members (table 1). There are two members in the study area. One is the second member (T_2b^2), which is composed of purplish-red fine-grained argillaceous siltstone and silty mudstone interbedded, the other is the third member (T_2b^3), which is composed of whitish-grey thin-bedded, medium-bedded and thick-bedded argillaceous limestone and medium-bedded to thick-bedded limestone interbedded, containing some marls. Quaternary deposits (Q) include mainly landsliding, collapsing and flooding deposits.

Table 1 Subdivision of the Badong group in the upper Yangtze area in China[1]

Stage		Member
Anisian T_2^1	Badong T_2b	T_2b^4
		T_2b^3
		T_2b^2
		T_2b^1

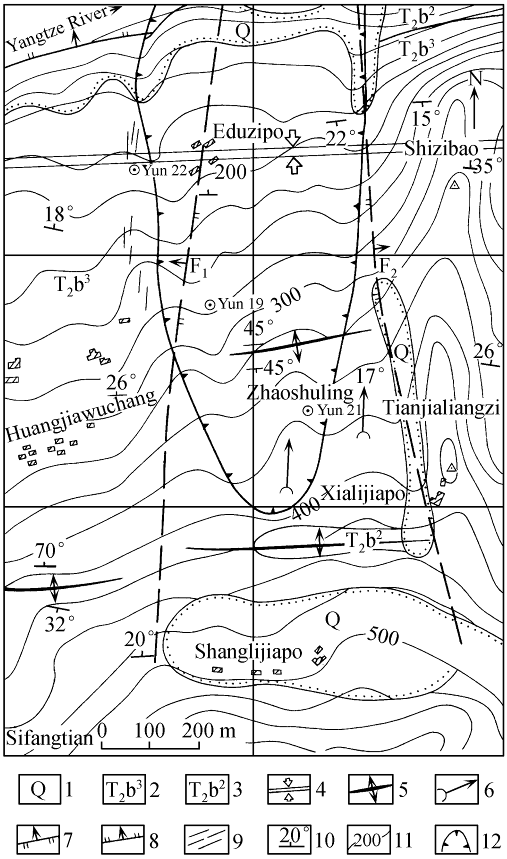

Fig. 1. Geological map of the study area. 1, Q; 2, T_2b^3; 3, T_2b^2; 4, axial trace of syncline; 5, axial trace of anticline; 6, small fold hinge; 7, reversed fault deduced by geophysical survey and its name; 8, normal fault; 9, reversed fracture zone; 10, occurrence; 11, formation boundary; 12, landslide boundary deduced by VSP, SRS and ES surveys.

The major structure in the area is characterized by near-E-W-trending multiple folds, a series of reversed faults as well as a great deal of joints and fissure systems. Guandukou syncline is a representative one among the fold structures. On the plan, the axis of the syncline strikes nearly E-W, its axial trace extending along the southern bank of the Yangtze River in the study area. On the section, the syncline manifests itself, on the whole, as an isothick symmetrical fold. On the two flanks of the syncline, there exist many unsymmetrical secondary interlayer folds, which were developed mainly in soft formations in T_2b^3 containing interbedded soft and hard rocks with different lithologies and formed by relative shear slide between different rock formations with different lithologies. Following the E-W folds, developed were near-E-W-trending reversed faults, bedding faults or bedding shear zones etc. Besides these E-W direction major structures, there also exist near N-S direction gentle folds striking across the southern flank of the syncline. Associated with these gentle folds, developed were near-S-N-trending reversed faults, among which Sizibao fault is a representative one. The investigation shows that the fault strikes nearly N-S and dips west at an angle of about 60° and that the fault triangle plane is shown on Sizibao in the topography. In addition to the faults mentioned above, in the area also developed were conjugate joint systems, fracture zones and various joints, as well as many structural indications such as gravitational creep-slippage, structure etc.

2 Choice and layout of geophysical surveys

To investigate and assess Zhaoshuling landslide, five geophysical methods including vertical seismic profile (VSP), shallow reflection seismic (SRS), electric sounding (ES), soil temperature (ST) and radioactive gas (RG) surveys, were designed. The layout of these surveys is illustrated in fig. 2.

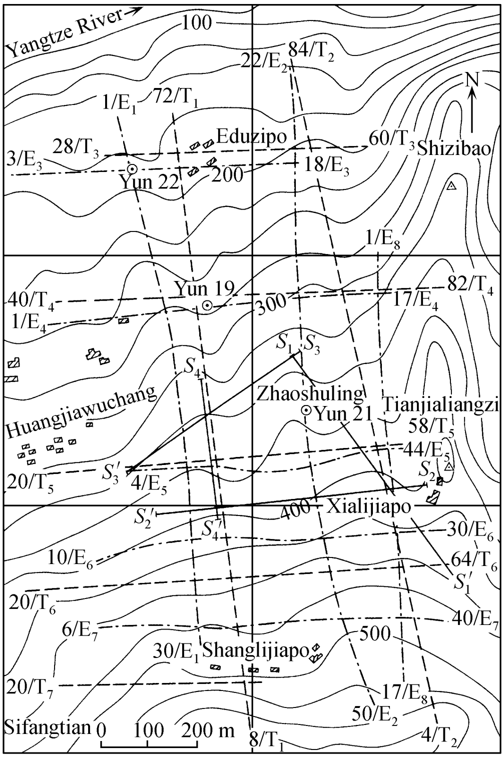

Fig. 2. Layout of geophysical survey. ⊙, Yun 19: borehole and its number for VSP survey; S_1-S_1', SRS survey line and its number; – • – •, ES survey line; $1/E_1$, station number/line number for ES survey; – – –, ST and RG survey line; $8/T_1$, station number/line number for ST and RG survey.

VSP survey was conducted in boreholes Yun 19, Yun 21 and Yun 22, with energy sources being located at points on lines oriented in N-S or E-W directions. Four SRS survey lines were placed in the vicinity of borehole Yun 21 and eight ES survey lines, as well as seven survey lines of ST and RG methods were placed in the area in a way that the distribution was approximately uniform and some of them passed by the three boreholes as much as possible, so that these surveys could cooperate well with each other.

The purpose of using VSP is to locate the distribution of formations and sliding planes as well as the elastodynamic moduli of rocks in the vicinity of the three boreholes. The method acquires the information of rocks and structures by analyzing down-going (direct) and up-going (reflected) wave fields. Down-going waves, having stronger energy, can reflect boundaries with significant changes of elastic properties. Up-going waves, on the other hand, being weaker, can reflect boundaries with small changes of elastic properties. Besides, transversal and converted waves (PS waves) can reflect nearly vertical fractures in two directions, parallel to or vertical to the ray path. According to Gardner et al.[2], bulk density (ρ) can be estimated empirically by the relationship

$$\rho = aV_{\mathrm{P}}^{1/4},$$

where V_{P} is the velocity of longitudinal wave and a = 0.31, when the unit of velocity is m/s. A group of successive elastodynamic moduli of rocks in the vicinity of the borehole, such as, rigidity modulus (G), Young's modulus (E), bulk modulus (K), shear modulus (μ) and Posson's ratio (σ) etc., can be derived from ρ and the velocities of shear and longitudinal waves[3—5]. It is therefore possible to locate these geological features such as weathered zones, sliding planes, formations and fractures etc. properly according to VSP data, thus providing foundations for the stability assessment of landslides.

SRS method, which locates sliding zones and boundaries between formations according to inphase axes that can be traced continuously and locates faults based on dislocation, stop or skew of inphase axes, was used to determine the distribution of formations, sliding planes and structures in the four SRS profiles. In the SRS survey, the offset is 40 m.

ES method can be used to locate the depth to sliding planes and the boundaries between different formations with different conductivities[6—8]. Schlumberger sounding was used, in combination with the above two methods, to locate the spatial distribution of the landslide body as well as the formation and structures in and out of it.

ST measurement, which measured temperatures in soils at a depth of 1 m, was used to investigate the character of seepage flow of groundwater and the degree of water saturation in the landslide body so as to provide useful information on assessment of the landslide[6, 8]. When the groundwater is seeping mainly through the sliding plane, if the survey is conducted in a scorching summer, the centre part of the landslide body will be characterized by higher temperatures and its boundary where groundwater seeps out will be characterized by lower temperatures, and if the survey is conducted in a cold winter, the centre part of the landslide body will be characterized by lower temperatures and its boundary where groundwater seeps out will be characterized by higher temperatures. These characteristics are the signs showing an unstable landslide.

The use of RG measurement which measured the radioactive intensity of ^{210}Po in soil samples was also to provide information for assessing the stability of the landslide. The principle is that in the stage that rocks are squeezed and creeped, the concentration of radioactive gases in the air of soil will be enhanced, because the rocks under it are being destroyed[8].

3 Data interpretation

3.1 Determination of landslide body, formations and structures

3.1.1 VSP method. Shown in fig. 3 are the profiles of up-going, down-going and shear waves in borehole Yun 19 when energy source is located at a point 10 m west of the borehole. It can be seen that at 19, 45, 63 m in the up-going wave profile, there exist strong reflected events and at 45 m there exist converted events. The inphase axes of these up-going events are disjointed, which indicates that at these zones rocks are stratified but that there exist fractures among these formations. In the down-going profile, longitudinal waves are complete, while converted waves incomplete, showing the existence of vertical fractures oriented in E-W direction because the source was located at a point on the line oriented in E-W direction. At the depth of 22—28, 45—62 m, thedown-going converted events are relatively distinct, which implies that there exist no more frac-

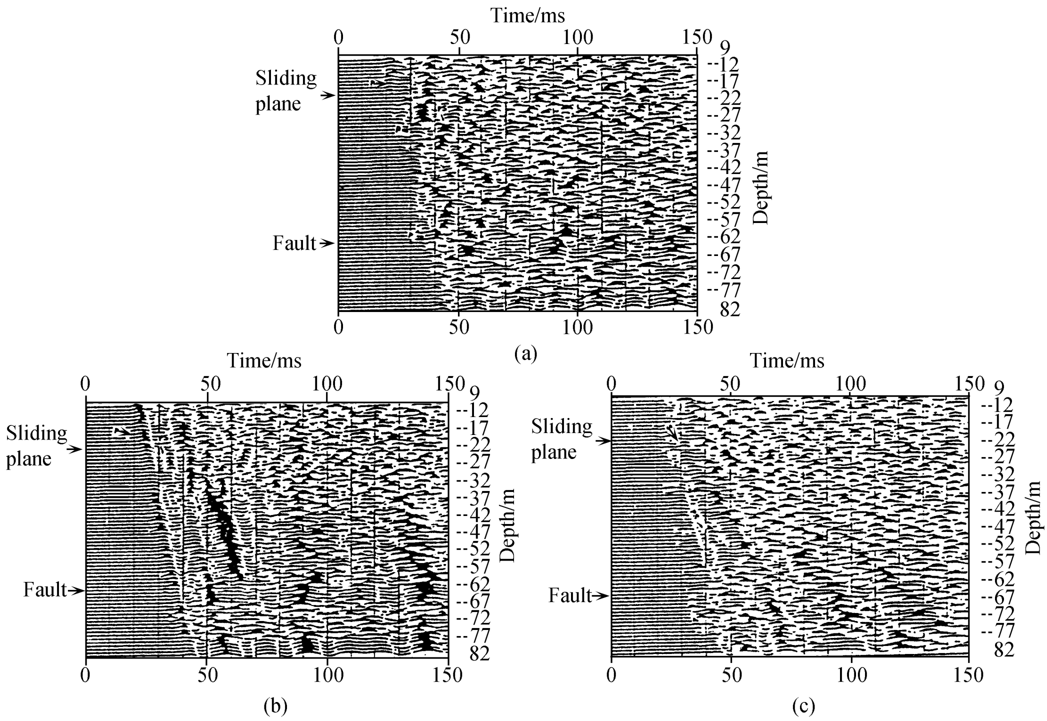

Fig. 3. Up-going wave profile (a), down-going wave profile (b) and shear wave profile (c) in borehole Yun 19.

tures. Beneath 62 m, the inphase axes of down-going events are curved and divergent, which shows that rocks are broken. According to the regional geology, the vertical fractures in E-W direction are controlled by layers.

A comprehensive comparison of elastodynamic modulus diagrams in the borehole and the borehole geological section is illustrated in fig. 4. Each elastodynamic modulus diagram is nor-

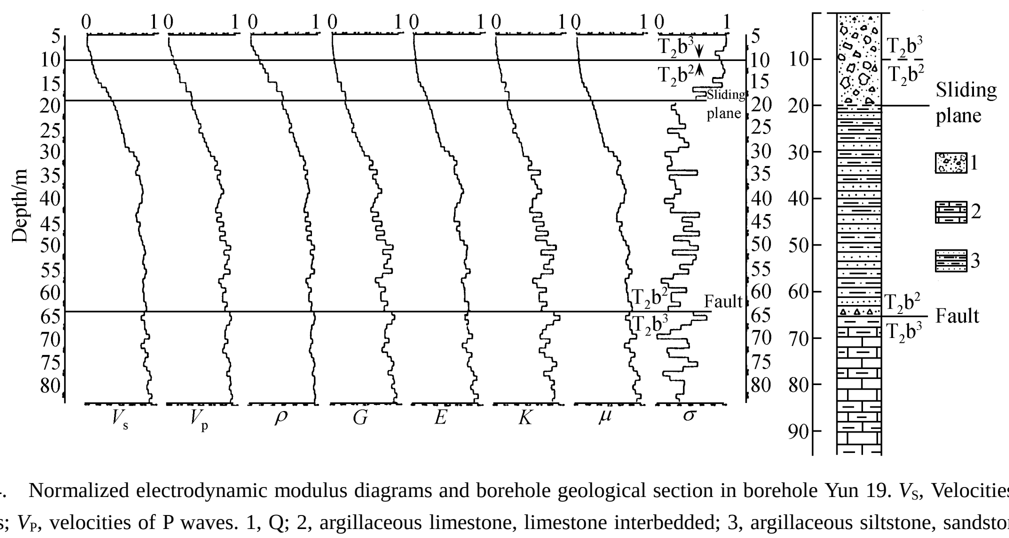

Fig. 4. Normalized electrodynamic modulus diagrams and borehole geological section in borehole Yun 19. V_S, Velocities of S waves; V_P, velocities of P waves. 1, Q; 2, argillaceous limestone, limestone interbedded; 3, argillaceous siltstone, sandstone interbedded.

malized with its maximal value. It is easy to see that in all indices, the sensitivity of Posson's ratio is the highest. According to the gradual change of all indices, we can deduce that the depth of weathered zone may reach 20—40 m deep. At the depth of about 10 m and 20 m, all the parameters have apparent changes, which implies that both the two places are probably boundaries of formations. At the depth of 65 m, all the parameters also have apparent changes, especially Posson's ratio increases rapidly, which indicates that rocks there are broken. These changes are more distinct and detailed than those in the profiles of up-going, down-going and shear events. Based on all the above interpretations, and the borehole geological section we can deduce that at the depth of about 10 m and 20 m are the boundary of T_2b^3 and T_2b^2 and the sliding plane respectively, and at the depth of 65 m, T_2b^2 and T_2b^3 are faulted contact. The fault, which is a reversed one, is named F_1.

The VSP data in borehole Yun 21 and Yun 22 are also interpreted in the same manner. It is deduced that in borehole Yun 21, the weathered zone is about 25 m thick and the sliding plane is situated at the depth of about 53 m, while in borehole Yun 22, no sliding plane or the boundary between T_2b^2 and T_2b^3 is discovered, and under the taluvium all rocks are limestone in which the development of cracks is also determined by VSP survey.

3.1.2 SRS method. The SRS profile of survey line S_3-S_3' is shown in fig. 5(a). It can be seen that above 20 m, there is no effective signal of seismic events, which indicates that the zone is a weathered one and that there exists no significant difference of elastic properties in rocks. At the depth of 30 m, there exists a reflecting boundary, combined with the interpretation of the VSP data in Borehole Yun 19, it can be deduced as the sliding plane. At the depth of 40 m on the side of S_3 and at the depth of 100 m on the side of S_3', there both exist events whose inphase axes can be traced continuously. Compared with the interpretation of the VSP data in borehole Yun 19, both locations can be deduced as the boundaries between T_2b^2 and T_2b^3. The boundary is obviously shown in all the four SRS profiles and is chosen to be the standard boundary in interpretation. In the middle of the profile, obvious dislocation and stop phenomena can be easily seen and the existence of a fault can

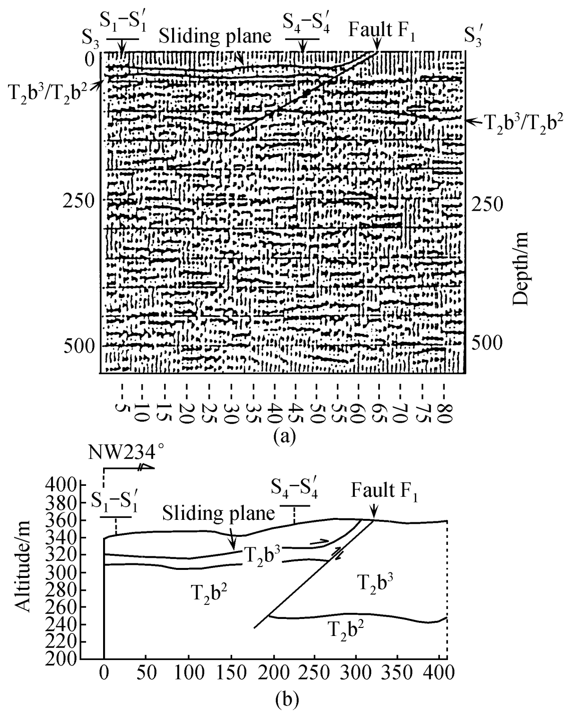

Fig. 5. SRS profile (a) and deduced lithologic and structural geological section (b) for survey line S_3-S_3'.

be deduced. The fault dips towards east approximately and is just the reversed fault F_1 deduced by the interpretation of the VSP data in borehole Yun 19. In formations T_2b^2 and T_2b^3, there are a lot of inphase axes which can be traced continuously though the continuity is not so good, indicating that both formations are not unitary. Based on the above interpretation, the deduced lithologic and structural geologic section is plotted (fig. 5(b)). The deduced lithologic and structural geologic sections for the other three survey lines are also obtained according to the interpretation of their SRS profiles. After interpretation of the SRS profile for line S_1-S_1', not only the sliding plane and the boundary between T_2b^2 and T_2b^3, but also a reversed fault located on the side of S_1' are deduced (cf. fig. 1). The fault dips towards west approximately and is named F_2.

3.1.3 ES method. Electric sounding curves were interpreted by using the reflectance profile technique. By interpretation of them, the imitative resistivity for each layer, which is approximately but not really equal to the intrinsic one, was acquired. The contour sections of the imitative resistivities for the eight ES survey lines were interpreted based on the interpreted results of VSP data and compared with the interpreted results of SRS data. In the interpretation, the contour sections for E_4, E_3 and E_1 survey lines passed by the above mentioned three boreholes were interpreted first and then those for the other survey lines.

Shown in fig. 6(a) is the contour section of the imitative resistivities for survey line E_4, in which borehole Yun 19 is at No.9 station. Compared with the interpretation of VSP in the borehole, it can be seen that the resistivities for weathered limestone is less than 100 Ωm, that for

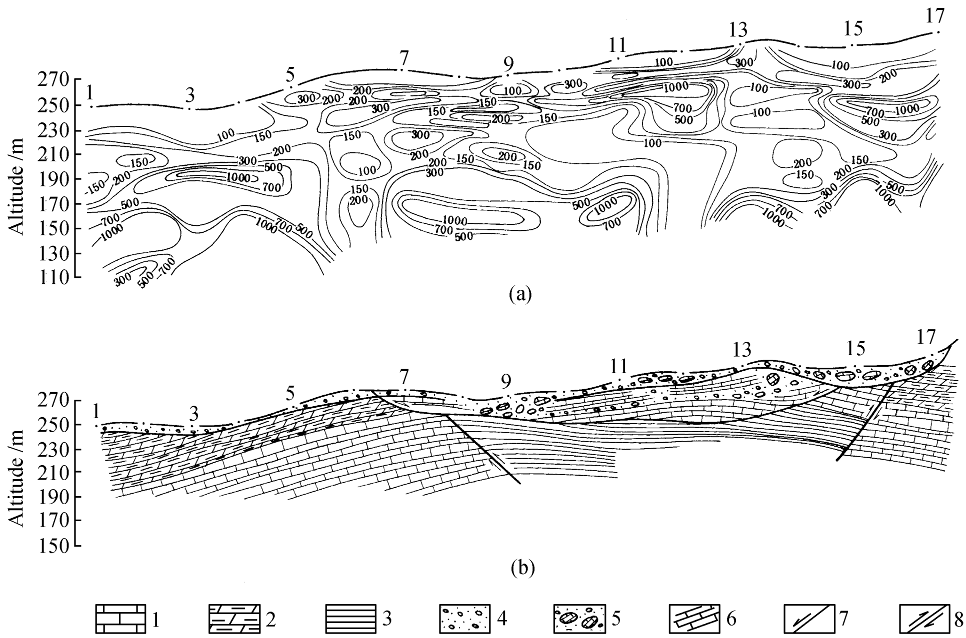

Fig. 6. Contour section of imitative resistivities (in Ωm) (a) and deduced geological section (b) for survey line E_4. 1, Limestone; 2, argillaceous limestone; 3, purplish-red mudstone; 4, soil and fine debris; 5, soil and coarse debris; 6, sliding mass; 7, sliding between layers; 8, sliding plane.

sandstone is about 100—200 Ωm, the sliding plane corresponds to the low resistivity zone with values less than 100 Ωm and the reversed fault F_1 corresponds to the low resistivity zone with values less than 150 Ωm. By tracing the low resistivity zone, the distribution of the sliding plane is delineated. The low resistivity zone corresponding to the reversed fault F_1 inclines to the east and the resistivities at its two sides are quite different, the distribution of the fault in the section is determined accordingly. Under stations 15, 16, another reversed fault inclining to the west is also determined using the same approach, which is the reversed fault F_2 determined by interpretation of SRS profile S_1S_1'. Besides, the boundaries between taluvium, T_2b^3 argillaceous limestone, T_2b^3 limestone and T_2b^2 sandstone are also located according to the values of imitative resistivities (fig. 6(b)).

The other contour sections of imitative resistivities were also interpreted in the same manner. After interpretation, the configuration of the landslide body, the distribution of formations and structures in and out of the landslide body are determined and a three-dimensional geological map is then plotted (fig. 7).

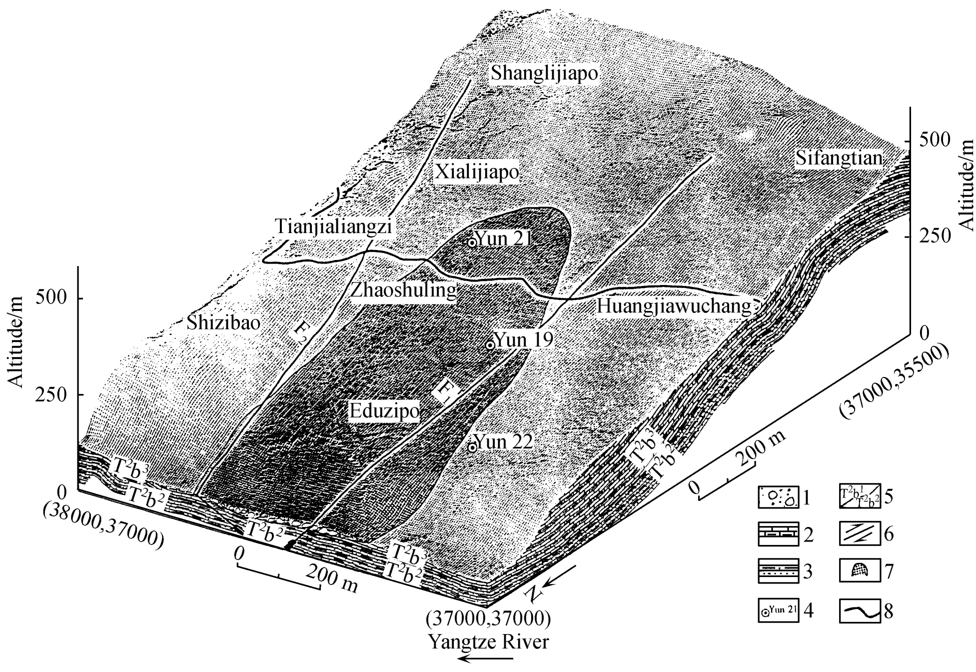

Fig. 7. Three-dimensional geological map of Zhaoshuling Landslide. 1, Q; 2, argillaceous limestone, limestone interbedded; 3, argillaceous siltstone, sandstone interbedded; 4, borehole and its number; 5, formation boundary; 6, reversed fault deduced by integrated geophysical survey; 7, limit of landslide; 8, simply-built highway.

3.1.4 ST measurement. After altitude correction and substraction of the normal temperature, which is the temperature at a base point in the central part of the landslide, measured ST data were used to draw the contour map of temperature anomalies (fig. 8). In the study area, soil temperatures are basically steady, with changes being less than about 1.5℃. The fact implies that the status of groundwater seepage flow in soil has no significant difference within the area, since soil temperatures are mainly controlled by the amount of seeping discharge and the temperature of water in the soil. Anomaly I is approximately coincident with the range of the landslide body deduced by VSP, SRS and ES surveys, and yet it is of low temperature. As the ST survey was carried out in a scorching summer, the existence of low temperature anomaly in the limit of the landslide body indicates that the groundwater does not seep mainly along the sliding plane, but in taluvium, and that the taluvium in the landslide has certain capacity of gathering groundwater seepage flows.

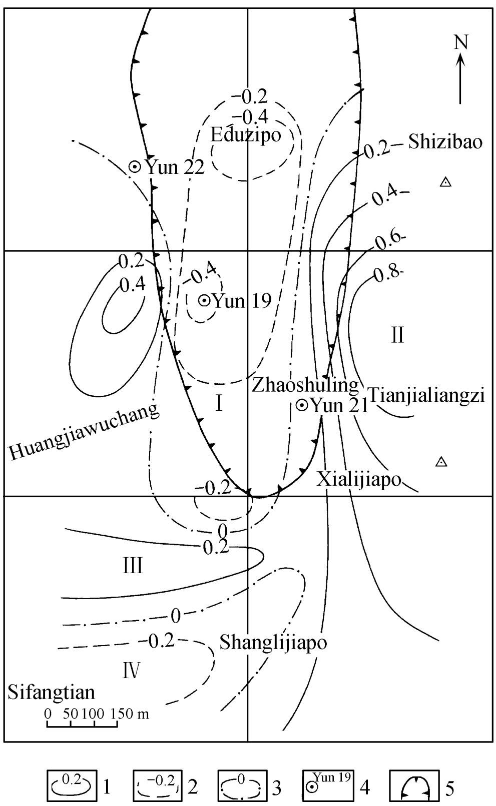

Fig. 8. Contour map of soil temperature anomalies (in ℃) in study area. 1, Positive contour; 2, negative contour; 3, contour with zero value; 4, borehole and its number; 5, landslide boundary deduced by VSP, SRS, ES surveys.

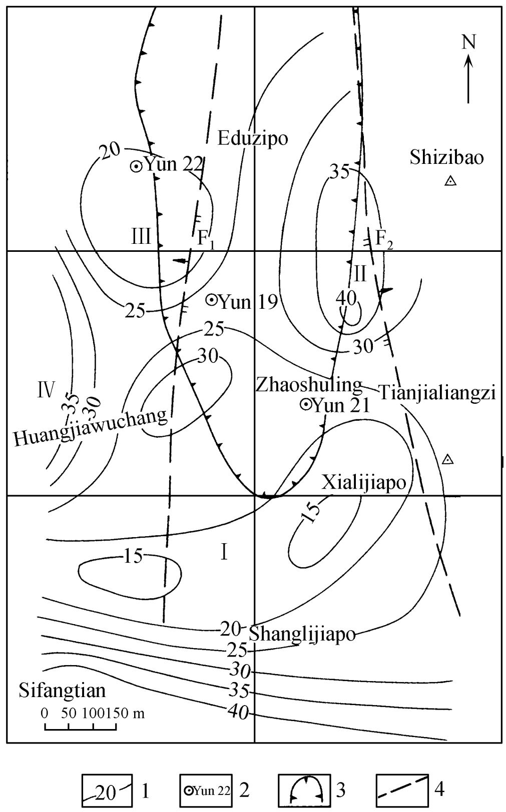

Fig. 9. Contour map of radioactive intensity of ^{210}Po (in pulse number/hour) in study area. 1, Positive contour; 2, borehole and its number; 3, landslide boundary deduced by VSP, SRS, ES, surveys; 4, reversed fault deduced by integrated geophysical survey.

3.1.5 RG measurement. The contour map of radioa ctive I ntensity of ^{210}Po (pulse number per hour) is shown in fig. 9. It can be seen from the figure that in the range of the landslide body, the intensity is less than in the surrounding area. The fact indicates that in the landslide body, there exist no deformation zones or fractures caused by apparent creep in rocks. The higher intensity of ^{210}Po of anomaly II on the east boundary of the landslide is probably related to the reversed fault

F_2. In the southern part of the area the increase in the radioactive intensity of ^{210}Po is probably related to the lithology of formations.

3.2 Assessment of the landslide

The integrated geophysical data interpretation shows that the landslide has the following character:

(a) The landslide body is about 1000 m long in N-S direction and 350 m wide in E-W direction, with an average thickness of about 35 m.

(b) The configuration of two flanks of the landslide is related to and partly controlled by the two near-N-S trending reversed faults F_1 and F_2.

(c) The sliding plane is controlled by lithologies and occurrences of formations.

(d) The sliding plane is mainly developed in argillaceous limestone and distributed along the boundary of T_2b^3 and T_2b^2 and partly across formations, suggesting that the landslide is one that has slided along the bedding plane of bedrocks and still preserves the original sequence.

There were two reasons for the formation of the landslide. One was the boundary conditions and the numerous weakness surfaces provided by early stage tectonic movements. The other was special narrow valley landform in the Three-Gorge Reservior area which was the essential conditions for producing gravity sliding. In the slip process of the landslide, as the overlain rocks lost stability and began to slip, the underlying rocks close to and between reversed faults F_1 and F_2 were drawn, thus forming a main deformable zone in deep formations, i.e. the main slipping zone.

However, the following data show that after undergoing a long-period geological action of millions of years, the ancient landslide is now still in a relatively stable stage:

(a) Though the area is a typical negative landform, the formation lain on the main sliding plane is thin, owing to the surficial geological actions in a long period. As to the geological situation at present, because of the unloading, the load on the sliding plane is greatly reduced, which is favorable to the stability of the landslide.

(b) In the zone of altitude 200—200 m, the main sliding plane is gently dipping so that the gravitational gliding effect is small. Besides, the landslide body is pressed on both flanks by surrounding rocks, owing to the existence of reversed faults F_1 and F_2. The distance between the two faults decreases from south to north, namely it decreases as the altitude diminishes, so that the clamping effect is large and plays an important role in the stabilization of the landslide body.

(c) Both interpretation of VSP and RG surveys show that the landslide is not in an apparent creep and press stage.

(d) ST survey shows that the groundwater seepage in the landslide flows mainly in the shallow part of the landslide body, not along the main sliding plane, which is helpful to the stability of the landslide.

To sum up, we consider that the landslide is now still in the stable stage and is an ancient landslide only.

4 Summary

The application of integrated geophysical survey to investigation and assessment of Zhaoshuling landslide is successful. The study provides extremely useful information for the complete and successful investigation and assessment of the landslide:

(a) The spatial configuration of Zhaoshuling ancient landslide body, and the spatial distribution of the formations and structures in and out of it is well determined by integrated use of VSP, SRS and ER surveys.

(b) The evidence that the ancient landslide is now still in a stable stage is provided by integrated use of VSP, SRS, ES, ST and RG surveys in combination with available geological data.

Based on the data of the detailed geological engineering survey and the integrated geophysical survey and a thorough study of it, the conclusion that the landslide is now in a stable stage and the area above 300 m altitude will be still stable even if the water in the Three-Gorge Reservoir is fully stored and can be properly used as common sites for civil construction is made by the Engineering Geological Party responsible for the investigation of the new site. The civil construction in the area is already in progress and the reversed faults F_1 and F_2 have been confirmed during excavation, proving the application and data interpretation of integrated geophysical surveys to be correct.

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