Integrated system of geophysical methods for shallow loose covering stratum exploration in the granite region in the northwest of Zhejiang Province, China

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Abstract. The major triggering factor of the collapses, landslides, and debris flow in the northwest region of Zhejiang Province in China is the shallow loose covering stratum with a thickness of dozens of centimeters to dozens of meters generated by the intensive physical weathering process of granite. Therefore, accessing a three-dimensional model of the slope structure covering by the shallow loose stratum and quantifying its thickness and spatial distribution are very important in deepening one’s understanding of the failure mechanism and distribution features and improving the efficiency of geohazard prevention and mitigation. This study applies high-density electrical method, microtremor survey, artificial transient surface wave method, and ground-penetrating radar to explore the slope structure covered by the loose stratum. By validating and comparing the results obtained through engineering geological drilling, an integrated system of the geophysical methods for the shallow loose covering stratum is proposed herein with greater precision and suitability for the granite region in the northwest of Zhejiang Province. This integrated system of methods consists of geophysical exploration, followed by drilling for validation. Each individual method in the system can be applied with suitability evaluation and recommended parameters. The proposed system could also properly void shortage when only an individual method is used. The major conclusions obtained in this study are as follows: (1) the accuracy of the high-density electrical method in the dry condition could reach 85% or above, and in the rainy season, the test should be conducted 48 h after the rainfall; (2) the microtremor survey and artificial transient surface wave methods can achieve good results in the case of a complex climate condition or a large-area detection; (3) the ground-penetrating radar method can be used to discover the loose covering layer thickness with good precision (less than 5 m); and (4) the integrated method system is more applicable when the ground slope is less than 30°.

Key words: granite region; shallow loose covering stratum; drilling exploration; Integrated geophysical exploration; feasibility evaluation

1. Introduction

The northwestern part of Zhejiang Province in China is located on the southeastern margin of the Lower Yangtze Block. During the Middle and Late Mesozoic, the magmatic intrusion in the area was intense, with a total area of approximately 1000 km². The unweathered granite has good engineering geological properties; however, the residual accumulation of the loose slopes formed by the weathered products is less stable, especially under the rainfall condition or artificial disturbances that could trigger various types of geological disasters (e.g., landslides, collapses, and debris flows). As one of the major controlling factors for the geological hazard development, the covering layer thickness has...
become a key important issue. Accordingly, comprehensive geophysical methods are used to effectively detect thickness, understand the development and distribution characteristics of regional geological disasters, deepen the understanding of the disaster formation mechanism, and improve the accuracy of geological disaster investigation evaluation. Hence, effectively supporting regional disaster prevention and reduction work is of great significance.

To solve this problem, many scholars have tried using the high-density resistivity method, ground-penetrating radar method, shallow earthquake method, and artificial surface wave method, among others, to detect the covering layer thickness. As a result, great progresses have been made. Scholars from Europe and the United States have used the three-dimensional (3D) high-density resistivity method to detect the Quaternary covering layer of geological hazard landslides and found the spatial distribution characteristics of the Quaternary landslide covering. Zhou et al.[1] applied the high-density resistivity method to monitor the rainfall infiltration process and landslide cover dynamic monitoring. Bachrach and Tapan[2] studied and evaluated the 3D ultra-shallow seismic reflection method to achieve a high resolution. The near-surface imaging method has also been applied to the cover layer detection and achieved good results. Meanwhile, Sargent and Goulty[3] used the 3D reflection seismic method to detect covering in areas where deep karst areas have developed. Consequently, they confirmed the effectiveness of the 3D seismic method in investigating potential surface collapses and other covering layer-related disasters.

In China, many researchers have applied relevant physical detection techniques to the cover layer thickness. Li et al.[4] applied high-density resistivity, two-dimensional profile inversion, and 3D inversion to explore the various layers and corresponding depths of the Mogangling landslide body. They effectively determined the burial depth of the bedrock and presented a drilling hole layout. Su et al.[5] used the high-density resistivity method to effectively determine the thickness, geological structure, and spatial distribution of the landslide cover under complex terrain conditions. They also summarized the details of the high-density resistivity method for detecting the terrain of the Quaternary cover using the thickness correction technology.

The previous results indicate that most studies used one single detection technology method to detect the cover layer. However, for areas with obvious terrain fluctuations, large changes in the cover layer thickness, complex types of causes, and overlapping effects of internal and external factors, comprehensive geophysical methods for the effective detection of the cover layer and research on related technical methods are still limited. Therefore, for the typical area covered by granite in the northwestern region of Zhejiang Province, this study selected the typical slope section of Luniao County in Hangzhou City, Zhejiang Province and applied the high-density resistivity, microtremor detection, artificial transient surface wave, and ground-penetrating radar methods. The methods for performing the covering thickness detection research put forward a comprehensive technical method of covering detection by combining with the “physical prospecting–drilling verification” in the granite area of northwestern Zhejiang to solve the covering thickness detection issues affecting the occurrence of geological disasters (e.g., inaccuracy and unsuitability of technical methods). The results of this study provide reference that is significant for performing covering sounding research in shallow coverage areas in the south-central southeastern coastal areas.

2. Introduction of geophysical survey technologies

2.1 High-density resistivity method

The high-density resistivity method is an electric exploration method based on the electrical differences of rock and soils. The calculated apparent resistivity profile is used for calculation and analysis according to the distribution law of the formation conduction current under electric field application. The resistivity distribution in the formation can be obtained to divide the formation and determine the abnormal formation (Figure 1).
2.2 Microtremor

Microtremor detection is a geophysical exploration method that is based on estimating the surface wave phase velocity using the vertical component of the seismic array microtremor signal and inverting the Rayleigh wave dispersion curve to obtain the S-wave velocity structure of the medium below the observation array. The most commonly used observation systems are three- or multi-point circular arrays, nested triangular circular arrays, and cross arrays (Figure 2).

2.3 Artificial transient Rayleigh surface wave

Surface waves can be divided into natural and artificial surface waves. Due to different shock modes, they can be further divided into steady-state and transient surface waves. The steady-state surface wave method obtains the propagation velocity of the Rayleigh waves of different wavelengths in the surface layer of the stratum by changing the source excitation frequency. The form is similar to the frequency sounding of the electrical method. On the contrary, the transient surface wave law involves the generation of a Rayleigh wave in a certain frequency range by hammering and dropping a weight or an explosive source. The Rayleigh waves of different frequencies in the record are separated through amplitude and phase spectrum analyses to obtain the frequency. The depth is inferred according to the first derivative method. The corresponding layer velocity calculation method is combined with the layer thickness for a comprehensive interpretation.

2.4 Ground-penetrating radar

The ground-penetrating radar transmits high-frequency electromagnetic waves to the ground through a transmitting antenna of T. Different media in the ground often have different physical characteristics (i.e., a geological radar mainly uses the difference in dielectric, conductivity, and magnetic permeability between the media). They have different electromagnetic wave impedances because of the different wave impedance on both sides of the formation interface. Electromagnetic waves will reflect and refract on the medium interface, and the electromagnetic wave pulse is reflected back to the ground. Its propagation path, electromagnetic field strength, and waveform will vary with the electrical properties and geometry of the medium, pass, and change. Therefore, one can infer the underground medium structure from the received radar reflection echo travel time, amplitude, and
waveform data. Figure 3 illustrates a schematic diagram of the principle of the ground-penetrating radar interpretation.

![Diagram of ground-penetrating radar](image)

**Figure 3.** Schematic working flow of the ground-penetrating radar method

The abovementioned methods can accurately detect the distribution of the cover layer thickness in an area under suitable conditions. However, granite areas have an unusually rainy climate; hence, large terrain fluctuations, shallow cover thickness, and vegetation coverage have been the major issues encountered when applying the geophysical detection method. With higher characteristics, the relevant data cannot be efficiently and accurately obtained if a certain detection technology method is used alone to detect the cover layer thickness. In following paragraph, we select a typical slope section for the application of the four abovementioned geophysical detection techniques for detecting the covering thickness, build an optimal combination of these geophysical combination methods, and effectively obtain the coverage thickness data in the area.

3. **Comprehensive geophysical detection of the covering thickness of the study area**

3.1 **Background of the study area**

The research area can be found northwest of Yuhang District, Hangzhou City, with convenient transportation and a relatively developed agricultural economy. The terrain is high in the west and low in the east, with hills and low mountains in the middle. The mountainous terrain is strongly cut. The slope is between 20° and 35°. The local undulation is large. Moreover, the vegetation is heavily covered.

The Quaternary strata mainly distributed in the study area consist of the upper groups of Meso-Pleistocene, Upper Pleistocene, and Holocene. Ranging from 3 to 22 m, the covering layer thickness significantly varies and generally increases from west to north east. The maximum thickness is nearly 100 m. The formation types of the covering layer are complex with marine and terrestrial sediments, granite full weathering, and strong weathering products. The porosity of rocks and the soil body is quite different. The resistivity difference is relatively obvious. Moreover, the propagation speed of the Rayleigh wave in such strata lays the foundation for the usage of high-density electrical method and other surface wave methods in combination to detect the cover layer thickness.
3.2. Overall plan of geophysical detection

3.2.1 Overall plan of detection layout

The detection line layout herein followed the principle of from known to unknown. On the basis of the previous geological disaster field survey results, the object detection line was selected for the typical slope section in the typical geological disaster in the key investigation area, slope section terrain, and human interference. This line is relatively small, thereby making the survey line pass through natural or artificial outcrops, drilling holes, and various geological profiles as much as possible.

3.2.2 Quality control of the detection

Multiple methods, namely high-density resistivity, microtremor detection, artificial transient Rayleigh wave, and ground-penetrating radar (GPR), were applied. Four high-density electrical survey lines were deployed by selecting the typical slope sections of two key geological disaster investigation areas in Shangougou village and west district of Quanchengwu village. The slope is the main line. The lateral cut slope is the auxiliary line. There are two active source surface waves, two microtremor survey lines, and two GPR survey lines. Figure 5 illustrates the plane layouts of the object detection lines.
3.3. Detection results

3.3.1 Principles of covering thickness interpretation

The electrical differences between different geological structures within the covering layer and the characteristics of the speed differences of various waves in the geological medium are the main reasons for interpreting the covering thickness using the high-density electrical method and the surface wave method. Relatively few data on the electrical characteristics can be found between different rocks and soils in the Quaternary covering in the study area. Many factors affect the apparent resistivity. The translation infers a realistic geological situation. Four methods were applied herein to detect the slope structure being covered by the loose stratum, namely the high-density electrical method, microtremor survey, artificial transient surface wave method, and GPR. The experimental and measured data showed that the phase velocity of the Rayleigh wave linearly increased with the increasing depth when the detected rock–soil medium was relatively uniform. In the presence of the interfaces of different media, the dispersion curve will have the characteristics of inflection point, slope change, and density change of the dispersion point. The change point is closely related to the depth of the interface between the two media, which can be based on the measured dispersion curve change point to infer the interface of underground lithology changes.

The inferred interpretation of the cover layer thickness can use the inversion resistivity value obtained by the high-density resistivity test on the typical outcrop profile and the measurement near the borehole based on the abovementioned resistivity and Rayleigh wave characteristics in rock and soil. The characteristics of the facies velocity change are used to infer and explain the stratum structure following the principle of interpretation from known to unknown.

3.3.2 Interpretation results of the high-density resistivity method

The high-density electrical method was mainly performed in the west of the village in the whole city. The area covered a small area with a steep slope and was close to a house. The cover was easy to slip off. It is a key geological disaster investigation area. Four high-density electrical measuring lines were arranged with a point distance of 2 m, and a total of 292 physical points. Figure 6 presents the interpretation results of each measuring line.

![Geological interpretation map](image_url)
Figure 6. Q1, Q2, Q3, and Q4 measuring line results based on the high-density resistivity method

The cross-sectional view of the inversion resistivity isoline of the survey line shows that the resistivity curves of the four survey lines have the same characteristics in the longitudinal direction. The trap is inferred as the Quaternary cultivated soil with relatively large pores in the shallow part. The resistivity is larger than 1150Ω.m. The resistance value of the middle thick layer is relatively low (i.e., from 1150Ω.m to 650Ω.m). This is inferred to be interpreted as a weathered layer with good water content. The resistivity with deep inversion tends to increase (i.e., larger than 1000Ω.m). The deep part is a high-resistance bedrock. Horizontally, the resistivity distribution is continuous.

3.3.3 Interpretation results of the microtremor method

The microtremor detection was mainly arranged in the Shangougou village area in the form of scattered points. The geological interpretation was obtained according to the phase velocity characteristics of the measured dispersion curve, such as the inflection point of the zigzag shape, change in slope, and change in the measurement point density.
Figure 7. Interpretation results of the microtremor methods for the WS08 and WS12 measuring points. The blue dots indicate the field measurements. The red dots indicate the fitting data.

Table 1. Interpretation results of the microtremor method in the Shangougou village.

| No. of borehole | Depth (m) | Layer thickness (m) | Phase velocity (m/s) | Shear wave velocity (m/s) | Geological properties | Note                  |
|-----------------|-----------|---------------------|----------------------|---------------------------|-----------------------|-----------------------|
| WS08            |           |                     |                      |                           |                       |                       |
| 8.9             | 6.4       | 290                 | 291                  | Silty clay with breccia   |                       |                       |
| 16.2            | 7.3       | 325                 | 324                  | Fully weathered granite   |                       |                       |
|                 |           |                     |                      |                           | Middle Weathered Granite | Predicted depth: 40 m |
| WS12            |           |                     |                      |                           |                       |                       |
| 3.5             | 3.5       | 240                 | 242                  | Silty clay with breccia   |                       |                       |
| 9.7             | 6.2       | 600                 | 697                  | Fully weathered granite   |                       |                       |
| 12.6            | 2.9       | 650                 | 726                  | Middle Weathered granite  |                       |                       |
|                 |           |                     |                      |                           | Middle Weathered granite | Predicted depth: 16 m |

3.3.4 Interpretation results of the transient Rayleigh surface wave method

The transient surface wave method was mainly applied in the west area of Wucheng village. Two survey lines existed, of which the Rs1-1 trend was approximately 18° northeast. Figure 8(a) exhibits a contour map of the Rs1-1 transient surface wave phase velocity contours in the west of Quanchengwu village. Figure 8(b) is a geological interpretation inferred map. The Rs1-1 section can be roughly divided into four layers from top to bottom. The first-layer phase velocity was less than 300 m/s. According to the drilling data, the shallow part is assumed to contain breccia silty clay. The phase velocity in the second layer was approximately 300–400 m/s. The reference borehole data were inferred to be fully weathered tuff. The third layer phase velocity was approximately 400–600 m/s. The reference borehole data were speculated to be strongly weathered tuff. The velocity was greater than 600 m/s. The body is no longer subdivide and is collectively called meteorological tuff.
Figure 8. Comprehensive results of the transient Rayleigh surface wave method for RS1-1

3.3.5 Interpretation results of the ground-penetrating radar method

The GPR method was used in Shangougou village. Accordingly, two test profiles were laid out. Ls1 was laid out from the foot of the slope to the top of the slope (approximately 60°) and was approximately 17 m long. Ls2 was laid out along the broken surface (approximately 0°) and was located in the north, passing the single-point microtremor measurement point WS01, which was approximately 12 m long. Figure 9 depicts the GPR interpretation results. The effective detection depth of the GPR was relatively shallow, not exceeding 5 m. Three interfaces were found between Ls1 and Ls2 below 5 m located at approximately 1.2 m, 2 m, and 2.8 m, respectively. The shallow 1.2 m was the surface cultivated soil. Approximately, 2 m is the internal layering of the cover. The interface between the cover and the strongly weathered granite was 2.8 m.
4. Validation of the geophysical detection results based on field exploration

The geophysical deep interpretation strata research follows the principle of interpretation from known to unknown, with reference to the rock formation data exposed by typical outcrops and boreholes using the geophysical properties of rock formations to speculate and interpret the rock formation distribution in unmeasured areas. The nine borehole data used in the study area mainly showed four engineering geological layers within the depth range of the detection target in the area: the first layer is breccia-containing silty clay; the second layer is completely weathered granite (or tuff); The third layer is a layer of strongly weathered granite (or tuff). The fourth layer is a layer of medium weathered granite (or tuff). To this end, the reliability of the interpretation results of the high-density electrical and surface wave methods was verified in combination with the drilling results.

4.1 Results validation of the high-density resistivity method

Five drill holes (i.e., ZK11, ZK15, ZK12, ZK14, and ZK13) were laid near the high-density electrical survey lines in the village west of the whole city to verify the reliability of the geophysical interpretation results. The Q2 line was laid with ZK15 and ZK12. The apparent thickness of the fully weathered covering and the thickness data of the thickness of the fully weathered covering exposed by the boreholes were compared for each borehole (Table 2).

The comparison and verification results showed that the high-density resistivity method can more accurately infer the cover layer thickness. The inference interpretation is more reliable. The accuracy and the reliability of the borehole verification located in the middle of the high-density electrical method profile were high. Located at the profile edge and affected by the boundary effect of the high-density electrical method itself, the interpretation results were inferred to be slightly different from the drilling results, albeit having small errors. The average accuracy of geophysical prospecting is 86.13%, showing that the high-density resistivity method is effective for measuring the cover layer thickness in the granite area in the northwest part of Zhejiang Province.

Table 2. Result verification of the high-density resistivity method by drilling exploration.

| No. of detection line | No. of Pole | No. of drilling | Predicted covering thickness (m) | Measured covering thickness by drilling exploration (m) | Accuracy (%) | Reliability degree |
|-----------------------|------------|----------------|---------------------------------|-------------------------------------------------------|--------------|-------------------|
| Q1                    | 15         | ZK11           | 2.8                             | 3.3                                                   | 84.85%       | Good              |
| Q2                    | 18         | ZK12           | 1.4                             | 1.5                                                   | 93.33%       | Very good         |
| Q2                    | 56         | ZK15           | 5.9                             | 6.9                                                   | 85.50%       | Good              |
| Q3                    | 56         | ZK14           | 2.8                             | 3.3                                                   | 84.84%       | Very good         |
| Q4                    | 28         | ZK13           | 2.3                             | 2.8                                                   | 82.14%       | Good              |
4.2 Results validation of the transient Rayleigh surface wave method

Four boreholes were arranged in the area of the surface wave measurement profile to verify the deep surface wave interpretation results of object detection. ZK11 and ZK12 were located in the west district of the city, while ZK7 and ZK8 were located in Shangougou village, thereby passing through the comprehensive measurement profiles of RS1 and WS12.

A comparison analysis of the profile and interpretation results of the data of the known boreholes of ZK11 and ZK12 and the surface wave data showed that the microtremor and transient surface waves had the highest recognition of the interface between the fully or strongly weathered rock and the moderately weathered rock. The borehole data were completely consistent. The bottom surface of the breccia-containing silty clay in the shallow surface layer exhibited a certain deviation from the comparison with the drilling data. The ZK11 hole floated up and down by 0.1 m, and the difference was small. The depth was deep at 0.5–0.6 m, but the borehole layering data corresponded well with the phase velocity contour of 50 m/s.

ZK7 was 9 m southeast of WS12, while ZK8 was 5 m west of WS12. Figure 7 shows the inversion results of WS12. The effective inversion depth reflected by the convergence of the dispersion curve at this point was 16 m and divided into four layers. The first layer was 3.5 m thick. The phase velocity change range was 0–240 m/s. The inversion shear wave velocity was 242 m/s. These results implied that the surface layer contained breccia silty clay. The second layer was 6.2 m thick. The phase velocity change range was 240–600 m/s. Furthermore, the inversion shear wave velocity was 697 m/s. These results indicate a fully weathered granite. The third layer was 2.9 m thick. The phase velocity range was 600–650 m/s, and the inversion shear wave velocity was 726 m/s. These values inferred a medium weathered granite (12.6 m in deep phase). The velocity was greater than 650 m/s. Lastly, the inversion shear wave velocity was 888 m/s, presumably showing medium-weathered granite.

The verification results showed that the surface wave method can better distinguish the interface between the middle weathered granite and the loose cover. Table 3 presents the specific comparison statistics, in which the depth error is computed as follows: (surface wave method infers the depth – drilling data revealing the depth) / drilling data revealing the depth.

Table 3. Statistic results of the transient Rayleigh surface wave method and drilling exploration.

| Drilling no. | Drilling velocity by the microtremor method (m/s) | Phase velocity by the Rayleigh wave method (m/s) | Depth of layer (m) | Error (%) | Layering thickness by the Rayleigh wave method (m) | Error (%) | Geological profiles |
|--------------|--------------------------------------------------|-----------------------------------------------|-------------------|-----------|-----------------------------------------------|-----------|---------------------|
| ZK11         | 450                                              | 600                                           | 3.4–14            | 3         | 3.2–14                                        | 0         | 0–3.3 m: silty clay with breccia |
|              | 200                                              | 300                                           | 0–2               | 15        | 0–2.1                                         | 19        | 3.3–14 m: fully weathered granite |
| ZK12         | 300                                              | 400                                           | 2–5               | 7.5       | 2.1–5                                         | 9.5       | 14–16 m: middle weathered granite |
|              | 450                                              | 600                                           | 5–10.5            | 0         | 5–10.5                                        | 0         | 0–1.7 m: silty clay with breccia |
|              | -                                                | -                                             | -                 | -         | -                                             | -         | 1.7–5 m: fully weathered granite |
|              | -                                                | -                                             | -                 | -         | -                                             | -         | 5–10.5 m: strongly weathered tuff |
|              | -                                                | -                                             | -                 | -         | -                                             | -         | 10.5–12.5 m: middle weathered granite |
|              | -                                                | -                                             | -                 | -         | -                                             | -         | 0–0.5 m: silty clay with breccia |
|              | -                                                | -                                             | -                 | -         | -                                             | -         | 0.5–9.1 m: fully weathered granite |
| ZK7          | -                                                | -                                             | -                 | -         | -                                             | -         | 9.1–15.3 m: fully weathered granite |
|              | 600                                              | -                                             | 9.7               | -6        | -                                             | -         | 15.3–20.6 m: middle |

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| Drilling no. | Phased velocity by the microtremor method (m/s) | Phase velocity by the Rayleigh surface wave method (m/s) | Depth of layer (m) | Error (%) | Layering thickness by the Rayleigh surface wave method (m) | Error (%) | Geological profiles |
|--------------|-----------------------------------------------|--------------------------------------------------------|-------------------|-----------|---------------------------------------------------------|-----------|---------------------|
| ZK8          | 600                                           | -                                                      | 9.7               | -17       | -                                                       | -         | weathered granite   |
|              | -                                             | -                                                      | -                 | -         | -                                                       | -         | 0.0–0.6 m: silty clay with breccia |
|              | -                                             | -                                                      | -                 | -         | -                                                       | -         | 0.6–13 m: fully weathered granite |
|              | -                                             | -                                                      | -                 | -         | -                                                       | -         | 13–14 m: fully weathered granite |
|              | -                                             | -                                                      | -                 | -         | -                                                       | -         | 14–15.5 m: middle weathered granite |

5. Suitability evaluation of different detection methods for covering layer thickness detection

The high-density resistivity, microtremor detection, and artificial transient surface wave methods were selected through a verification of the interpretation results of the four abovementioned detection methods and the drilling data combined with the typical slope, geological, and geomorphological characteristics of the study area. The advantages and disadvantages of each method were analyzed based on the different combinations of the GPR method. A set of geophysical methods for the covering layer thickness detection in the granite area in the northwest region of Zhejiang Province was also summarized.

The high-density resistivity method is recommended because of its mature method system and wide application examples. It is preferred in the case of a small-area measurement. The surface wave method is portable and has high construction efficiency. Meanwhile, the surface wave method is recommended for a large-area measurement work. The GPR method can be used when the ground is flat and open, and a high resolution is required for the shallow parts. Each geophysical prospecting method has its own advantages and disadvantages (Table 4). Using comprehensive geophysical prospecting methods can improve the depth accuracy of geophysical prospecting and meet the needs of covering layer thickness detection in the granite area in northwest Zhejiang.

**Table 4.** Comparison of various geophysical detection methods applied in shallow covering.

|                     | High-density resistivity method | Microtremor method | Transient surface wave method | Ground-penetrating radar method |
|---------------------|--------------------------------|--------------------|-------------------------------|---------------------------------|
| Depth               | 0–30 m                         | 0–40 m             | 0–25 m                       | 0–5 m                           |
| Advantages          | The method is mature and has high accuracy. It is sensitive to the cover layer interface with a thickness of 0.5 m and above and suitable for the detection of local key parts. | The equipment is light, green, and efficient. The difference in the surface wave velocity can make up for the deficiencies of the high-density resistivity method under saturated water. Area observation can be performed. | It is portable and efficient. The shallow part has a high resolution and not affected by the saturated water condition on the ground like the microtremor. | Portable and efficient The image is intuitive, true, and easy to identify. High resolution |
| Disadvantages       | In a saturated ground, the effect is not obvious when the electrical difference is small. The working efficiency is also relatively low. | Only a few application examples have been introduced. The interpretation accuracy is affected by the accuracy of the known physical property parameters. | The detection depth of the artificial hammer source is shallow. The interpretation accuracy is affected by the accuracy of the known physical property parameters. | The signal attenuation is fast, and the detection depth is small. It is easily affected by the collection environment. The superconducting medium (aqueous medium) greatly influences the detection result. |

The precipitation in the granite area of northwest Zhejiang is intensive. The area is in the precipitation period for many months every year. The surface moisture content and the saturation degree greatly
affect the efficiency of the high-density electrical method for detecting the coverage of the shallow coverage area. In the case of the covering combination, within 1 day after the precipitation, the inversion resistivity value is significantly reduced by the local precipitation saturation, especially in the absence of a fully weathered granite formation. The inversion resistivity of the covering layer decreases from 500 to 2000 $\Omega\cdot$m to 200–800 $\Omega\cdot$m. Moreover, the difference is close to 1000 $\Omega\cdot$m, leading to a certain degree of inference that would explain the depth error increase of the cover layer interface. Therefore, in the precipitation condition, the high-density electrical test should be performed at least 48 h after the precipitation. Accordingly, the high-density electrical method infers that the interpretation results are in a good agreement with the drilling results. The surface wave method is basically unaffected by rainfall, but requires that the terrain within the array is free of drastic terrain fluctuations and lithological differences and that a strong directional noise interference should be avoided as much as possible. The corresponding geophysical detection methods must be refined according to the results of the physical exploration work performed in the research area and to the geomorphological characteristics of the granite area in northwest Zhejiang (Table 5).

**Table 5.** Recommended methods for covering stratum detection in the granite area.

| Geological features                                                                 | Recommended methods                      | Note                                                                 |
|-----------------------------------------------------------------------------------|------------------------------------------|----------------------------------------------------------------------|
| Cover layer thickness: less than 1 m                                              | Ground-penetrating radar                 | The high-density electrical method must avoid construction during the rainy season. If precipitation is encountered during the construction process, construction should be done after 48 h of precipitation. |
| Detection depth: less than 5 m                                                    |                                          |                                                                      |
| Slope angle: less than 30°                                                        |                                          |                                                                      |
| Site: open and not covered by a large area of tall vegetation                      |                                          |                                                                      |
| Cover layer thickness: greater than 1 m                                            |                                           |                                                                      |
| Detection depth: 5–30 m                                                            | Microtremor method                       |                                                                      |
| Slope angle: should not be greater than 30°                                        | Transient surface wave method            |                                                                      |
| Acquisition system: can be installed in a single slope                             | High-density electrical method           |                                                                      |
| (length of the high-density electrical method measurement line: should not be less than six times the sounding) |                                          |                                                                      |
| Cover layer thickness: greater than 1 m                                            |                                           |                                                                      |
| Detection depth: greater than 30 m                                                 | Microtremor method                       |                                                                      |
| Slope angle: of should not be greater than 30°                                     |                                          |                                                                      |
| Terrain: without severe undulations                                                |                                          |                                                                      |

6. Conclusions

Using high-density resistivity and surface wave methods, this study investigated the cover layer thickness of two typical slopes in Coral Bird Town, Yuhang District, Hangzhou City. The thickness distribution of the main engineering geological layer in the study area was speculated, and the granite area in northwest Zhejiang was analyzed. The combination of geophysical and geophysical methods for the cover layer thickness detection provide the following conclusions and suggestions:

1) The high-density resistivity method can effectively detect the cover layer thickness when the electrical difference between the covering layer and the underlying stable bedrock is significant. The comparison with the drilling exploration results showed that the high-density electrical method inference results were basically consistent with the borehole exposure. Moreover, the evaluation inference interpretation accuracy was as high as 86.13%.

2) The surface wave method detected well the cover layer thickness of the granite region in the northwestern part of Zhejiang Province. In the case of the same survey line length, the surface wave method can effectively detect the depth of the higher density resistivity method. The transient surface wave (active source) and microtremor (passive source) methods also exhibited a higher similarity in profile results.
(3) A comprehensive analysis of the application effect of the four types of cover layer thickness detection methods applied in the granite area of northwestern Zhejiang was performed herein. The results showed that the high-density electrical method can reflect well the electrical characteristics of the cover layer in the shallow coverage area to effectively delineate the cover layer thickness. The saturated surface state had a certain influence on the detection accuracy. The microtremor detection can effectively obtain the velocity information of formations of different depths through a combination of different radius sizes and divide the formation structure, which can better distinguish the shallow engineering geological interface. The method has advantages of green and high efficiency. The transient surface wave detection was similar to the microtremor and can better divide the shallow stratum structure. The signal-to-noise ratio was high, but the hammering source energy was limited, and the exploration depth was mostly less than 20 m. An exploration blind zone for the stratum, which was less than 1 m, was found when the surface wave method was used. The GPR can better distinguish the stratum structure of this depth, which can complement it. However, the detection depth of the GPR is limited. Furthermore, the low-frequency antenna is not conducive to the construction of tall vegetation coverage areas.

The following suggestions are also made based on the study results:

(1) A small study area must be meticulously measured and must be not be affected by the weather. The high-density resistivity method is preferred for detection in this area.

(2) The surface wave method is not affected by the saturated surface state and has good vertical layering ability and advantages of green and high efficiency; hence, it is suitable for large-area detection.

(3) The GPR is suitable for gently open areas. The 100–250 MHz antenna is recommended for use in areas with high vegetation coverage like the Hangzhou Cormorant Town.

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