An underground information visualization method and its deep shaft application

S C Zhao¹, X J Li¹, Y Shen¹*, and F Y Cheng¹

¹ Department of Geotechnical Engineering, Tongji University, Shanghai, 200092, China

shenyi@tongji.edu.cn; ORCID:0000-0001-6539-4918

Abstract. With the development and utilization of underground space, the emergence of visualization technology and the increasing amount of associated information, underground engineering information visualization has become increasingly relevant and important. However, at present, information visualization problems are commonly encountered during the process of visualization expression of underground engineering information. These problems include monotonous visualization form, color matching ignoring visual perception, and spatial occlusion reducing information readability. These issues not only reduce the visualization effect and the efficiency of information acquisition, but they are also associated with certain safety issues. In view of the problems that exist in underground engineering information visualization, the aim of this paper was to provide a theoretical basis applicable to cases in order to improve the visualization expression of underground spatial information. This paper conducted research from two perspectives: the visualization principle and the visualization method. The No. 1 shaft deep foundation pit of the Shanghai hard X-ray project was used as the engineering background in order to realize the visual display, analysis, and early warning of the engineering data of the foundation pit project.

1. Introduction

Generally, underground engineering data come from design drawings, document reports, sensors, and other acquisition equipment and involves many stages including investigation, design, construction, operation, and maintenance[1]. As construction progresses, the attention of the engineers gradually shifts from the static drawing data in the investigation and design stage to the dynamic data in the construction and monitoring phases that change over time. By integrating and classifying multi-source and multi-form data, the underground engineering data that needs to be visualized are divided into two categories: static geological and structural data[2,3], and dynamic construction and monitoring data[4,5].

In real-life underground engineering projects, the data types are complex, and the amount of information is large. There are three problems in visualization research: (1) the visualization form is monotonous, and the random use of colors causes poor visualization, (2) when simulating a dynamic construction process with a three-dimensional (3D) model, the occlusion phenomenon leads to a decrease in the observability of the internal construction, and the visual analysis of monitoring information lacks an effective correlation with the construction conditions, and (3) visualization
results do not consider the expression of information, and information acquisition efficiency is quite low.

In response to the above problems, this paper explores universally applicable underground engineering information visualization principles from three perspectives: visualization effect, transparency adjustment, and information integrity, and presents visualization methods for major underground engineering information, including geology, structure, construction, and monitoring data.

2. Visualization principle

2.1. Visual coding principle

Visual coding refers to the use of a geometric signature and visual channels to establish a mapping relationship between data and images\(^6,7\). The geometric signature represents geometric elements in visual graphics. The visual channel represents the mapping relationship between the values of data attributes and the visual features of the geometric signature. The visual channel controls the visual presentation of the visual carrier and is closely related to the final visual effect. Based on the theory of visual coding and color design\(^8\), this paper summarizes the visual coding visualization principle applicable to underground engineering information, as shown in Figure 1.

(1) Category data of underground engineering emphasizes individual differences and highlights differential visualization effects. The position, hue, transparency, and shape visual channels are used to encode category data.

(2) Ordered data of underground engineering mainly express the value of the object, or reflect its internal order, and this usually has a quantitative continuous numerical interval. The brightness, saturation, and size visual channels are used to encode the ordered data.

![Figure 1. Visual coding principle of underground engineering information.](image)

2.2. Color designing principle

As a special visual coding channel, color is superior to other visual elements in terms of expressing data at a structural level, attracting human attention, highlighting key information, and improving esthetic value, etc.\(^9\) Therefore, this paper proposes the color designing principle from three standpoints: the color selection scheme, color warning, and color harmony.

2.2.1 Color selection scheme based on hue. Since the hue, saturation, value/hue, saturation, lightness (HSV/HSL) color space is close to the human perception of color\(^10\), the color selection scheme in this paper is based on the HSV/HSL color space with three visual channels separated from hue, brightness, and saturation. In order to make color selection more convenient, and taking the example of HSV color stereo, hue is used as a dimensionality reduction factor and converts the color space into a plane coordinate system with brightness and saturation as the coordinate axes. According to the color
selection order of Figure 2(a), the color that meets the visual design intent of the underground engineering information is obtained.

![Image](image-url)

**Figure 2.** Color designing schematic diagram: (a) color extraction method based on hue, (b) early-warning color “red” extraction. HSV, hue, saturation, value.

### 2.2.2 Principles of early-warning color selection
Due to the fuzziness of color language expression, color semantic description with a certain symbolic meaning can often map a variety of colors, and this undoubtedly brings great difficulty to color selection. In order to highlight important information, the color with high brightness (V = 100%) and high saturation (S = 100%) can emphasize the visual effect and produce more intense stimulation[11]. Therefore, this paper selects “red,” “yellow,” “orange,” and “blue” with high brightness and high saturation for color visual warning of the construction progress and monitoring data.

### 2.2.3 Color harmony scheme
The essence of color harmony is the process of changing one or more attributes of color regularly in order to achieve a harmonious visual effect of multiple colors [12]. This paper provides a color matching scheme for underground engineering information visualization through hue (brightness + saturation) reconciliation and multi-color (hue + brightness + saturation) reconciliation.

### 2.3. Transparency-construction state visualization principle
Underground engineering construction data have certain spatial and temporal characteristics. With the progress of construction, the construction data are updated dynamically [13]. In order to reduce the visual occlusion of the peripheral structure, and to facilitate the observation of the overall construction progress of the project and the construction state of the current working surface, the transparency-construction state visualization principle is proposed in order to describe the construction state of underground engineering at different time nodes, as shown in Table 1.

| Object                  | State          | Visualization principle | Legend          |
|-------------------------|----------------|-------------------------|-----------------|
|                         |                | Transparency | Display         |                 |
| Rock-soil mass          | Excavated      | Opaque                  | Non-display     |                |
|                         | Not excavated  | Opaque                  | High grey value |                |
| Main structure          | Internal structure | Opaque              | Mid grey value  |                |
|                         | Exterior structure | High transparency | HSV (120,100,100) |                |
|                         | -              | Non-constructed        | Non-display     |                |

### 2.4. Integrity visualization principle
In order to display information as far as is possible in a limited visual screen, and improve the efficiency of information acquisition[14, 15], this paper proposes the principle of underground engineering information integrity visualization. This principle takes underground engineering objects as the core elements, and reflects the integrity expression related to the core elements of visualization.
from three points of view: time information, spatial information, and attribute information, as shown in Figure 3. Try to display information in the same view as much as possible to ensure completeness. If necessary, it can also be displayed in multiple parallel views.

**Figure 3.** Principle of underground engineering information integrity visualization.

### 3. Visualization method

In view of the monotonous form of underground engineering information visualization, and the lack of intuitive visual presentation effect, this paper considers the influence of visual coding and color design principles on the visualization effect, and further combines various data visualization methods to express underground engineering geology, structure, construction, and monitoring.

#### 3.1. Geological data visualization

In order to enhance the visualization effect, this paper uses the sunburst chart and 2D + 3D geological model to visualize the relevant geological data along the underground engineering site.

The classification information of soil layer, geological age information, and other geological data is classified and processed, and a data structure with a certain relationship level is formed. The sunburst chart can be used to express such geological information, as shown in Figure 4(a), and the color value of the corresponding soil is mapped to the 2D + 3D geological model.

Due to the spatial characteristics of geological data, it is necessary to establish 2D geological graphics or a 3D geological model as a visual expression carrier. In order to form a simple visual effect, according to the form of different geological objects, the geological objects are selectively expressed in 2D + 3D views, as shown in Figure 4(b).

**Figure 4.** Geological data visualization: (a) soil layer classification sunburst chart, (b) soil layer distribution information of the 3D geological model.
3.2. Structural data visualization

The structural data involved in underground engineering mainly include the design results related to the engineering subject, obtained predominantly from the design drawings. In order to express structural data in an intuitive form, this paper proposes a multi-level view-based visualization method using a 2D–3D structure model, as shown in Figure 5.

**Figure 5.** Structure information multi-level view visualization method.

3.3. Construction data visualization

In order to show the construction progress information intuitively, this paper uses a Gantt chart to compare and analyze the actual progress with the planned progress and identify the progress deviation, as shown in Figure 6. According to the relationship between the progress deviation and the time parameters in the network diagram, a visual grading early warning system of construction progress based on color psychology is proposed, as shown in Figure 7.

**Figure 6.** Gantt chart of construction progress.
3.4. Monitoring data visualization

In order to more intuitively reflect the change trend of monitoring data in the process of underground engineering construction with a change of color, this paper proposes the color mapping rule of monitoring data based on the hue blending method, as shown in Figure 8. This rule is suitable for the visual expression of the cumulative value and the deformation rate of the monitoring data.

In underground engineering monitoring, different monitoring projects are often needed for different engineering objects. In this paper, the monitoring projects are divided into four categories: structural internal force monitoring, structural deformation monitoring, deformation monitoring of surrounding buildings (structures), and the monitoring of surrounding water and soil. A variety of visualization methods are used to visualize the cumulative monitoring values, as shown in Figure 9.

4. Engineering application

The construction site of the Shanghai high repetition rate hard X-ray free electron laser (SHINE) is located in Zhangjiang Science City and is composed of multiple tunnels and five shafts. The No.1 shaft is located at the front of the device and is a long, narrow, deep foundation pit project with an inner net size of 20 m × 70 m. In order to verify the principle and method of underground engineering information visualization proposed in this paper, the underground engineering information visualization method is applied to this case to realize the visualization display, analysis, and early warning of the engineering data of the foundation pit project.

In terms of the expression of geological information, the soil layer classification sunburst chart, geological age sunburst chart, soil property circle map, and 2D and 3D geological models are arranged in the same data panel as several parallel views. The geological data panel takes the soil geological object as the key index to realize the linkage visualization of geological data. The visualization effect diagram is shown in Figure 10(a).
In terms of the expression of structural information, based on the established multi-level 2D + 3D foundation pit structure model, the structural object of the foundation pit is taken as the index sign, and the related design results of the foundation pit structure object are displayed in the form of a 3D view, 2D plane, and profile view map, as shown in Figure 10(b).

In terms of the expression of construction information, the visualization grading early warning system is integrated into the visualization results of the construction process. The construction objects and construction progress information are taken as the key indices. The associated Gantt chart and the 3D view reflect the change of progress information with the construction process dynamically, as shown in Figure 10(c).

In terms of monitoring information expression, the monitoring object and time information of the foundation pit are used as the main index signs, and the 3D view, the time bubble diagram/time thermal diagram, and the monitoring curve are dynamically correlated, as shown in Figure 10(d). The 3D view shows the synchronous change of the monitoring cumulative value with the excavation. It reflects the time and spatial distribution characteristics of all the measuring points for one or multiple monitoring contents and realizes the rapid positioning of the cumulative value warning. The monitoring curve is helpful to analyze the cumulative value. The time bubble diagram and time thermal diagram are used to visually display and warn of the deformation rate of multiple measuring points.

![Multi-view linkage effect map of deep foundation pit engineering information visualization](image)

**Figure 10.** Multi-view linkage effect map of deep foundation pit engineering information visualization: (a) geological data, (b) structural data, (c) construction data, (d) monitoring data.

5. Conclusion
This paper has systematically studied underground engineering information visualization methods in order to address the following problems: monotonous underground engineering information visualization form, color matching ignoring visual perception, spatial occlusion reducing information readability, and low information acquisition efficiency. The main conclusions are:

(1) The four universal underground engineering information visualization principles have been summarized. In terms of visualization effects, the principles of visual coding and color design have been proposed, and the applicable scenarios of the visual channel and color selection schemes have
been summarized. In terms of transparency adjustment, the principle of transparency-construction state visualization has been proposed, and the transparency visual channel was used to enhance the readability of construction dynamic information. In terms of information integrity, the principle of visualization of information integrity and a visual interaction method of multi-view association have been proposed.

(2) The visualization methods of different types of underground engineering information have been summarized. In view of the geological data, this was expressed using the method of sunburst chart + 2D–3D model. Regarding the structural data, a 2D + 3D structural model visualization method based on multi-level views has been proposed. With regard to the construction data, it was expressed using the Gantt chart and the visual grading warning system of construction progress based on color psychology. For the monitoring data, color mapping rules and various visual analysis methods have been proposed.

(3) The principle of underground engineering information visualization was applied to the deep foundation pit engineering of the SHINE project. With regard to the geological, structural, construction, and monitoring data, the specific multi-view linkage effect maps were given in order to realize the visualization display, analysis, and early warning of the deep foundation pit engineering information, and the feasibility of the principle of underground engineering information visualization is verified.

6. References

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