15 Apr 2004, 1:00pm - 2:45pm

A FEM Seepage Analysis for Upstream Cofferdam of Xiluodu Hydraulic Power Station

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Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

A FEM SEEPAGE ANALYSIS FOR UPSTREAM COFFERDAM OF XILUODU HYDRAULIC POWER STATION

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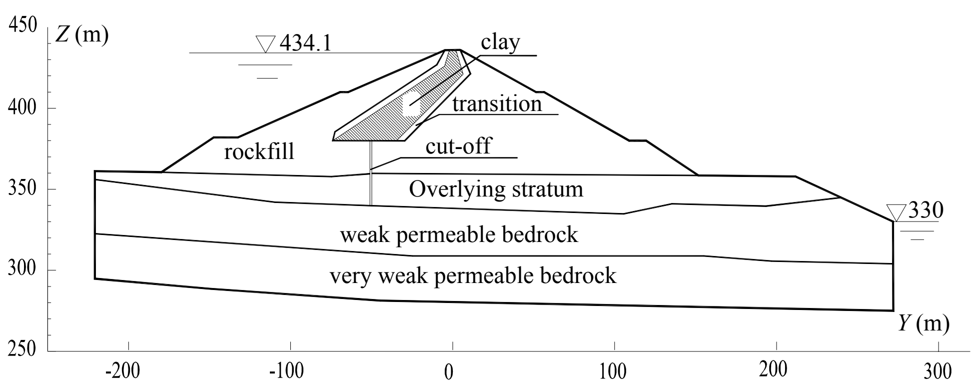
ABSTRACT

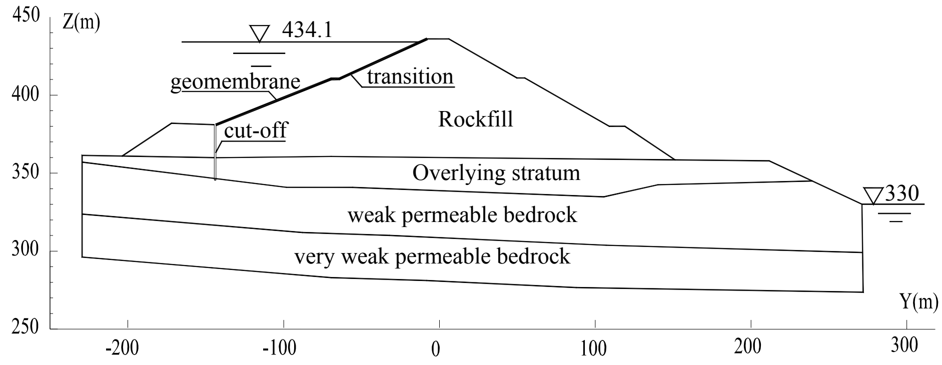
The upstream cofferdam of Xiluodu hydraulic power station project, with height of 72 meters, is designed as the main body of the project. It is characterized by its high retaining water head, short construction period and complex geological conditions. Presented in this paper is a three-dimensional FEM analysis used to investigate the seepage behavior of the upstream cofferdam for two different design schemes. In the analysis, the cracks in cut-off wall which may be caused in construction are also properly considered. Based on 3D seepage model of saturated-unsaturated flow for non-uniform soils, a fixed-mesh FEM is used in the seepage analysis of the upstream cofferdam. As the results of the analysis, the distribution of water head and discharge of seepage are obtained and compared. The seepage stability of the cofferdam is analyzed to be safe enough based on the new concept called critical gradient zone.

INTRODUCTION

Xiluodu hydropower station, which is located at the Jinshajiang River in southwestern China, is another great hydraulic project after Three-Gorge Project. An upstream cofferdam with height of 72 meters has been designed as the main body of the project. It is characterized by its high retaining water head, short construction period and complex geological conditions. The cofferdam itself has a complicated structure with very quite difference among the permeability of the materials of different fill zones. After preliminary analysis, two primary design schemes of seepage-proof structure, including a soilaggregate sloping core wall and a geomembrane sloping wall, were suggested and then required to be further evaluated which one better in the seepage control. Fig. 1 shows the simplified maximum cross section of the cofferdams with two different seepage-proof structures for the seepage analysis. The main body of the cofferdam is constructed with rockfills and gravels with good hydraulic conductivity. The soilaggregate sloping core or geomembrane sloping wall is suggested as body of seepage-proof structure. The cofferdam's foundation is composed of an overlying stratum and bedrock. The overlying stratum is mainly made of sands and gravels, probably forming a good path for seepage. A concrete cut-off wall is therefore built in the stratum, which is same for the two schemes. The bedrock is divided into weak permeable layer and very weak permeable layer according to their permeability. The geological profiles of the cofferdam are shown in Fig. 2. It could be seen that the distribution of material zones of the foundation is of three-dimensions, and as a result, 3D FEM seepage analysis is used in this paper.



a) Cofferdam with a soilaggregate sloping core wall



b) Cofferdam with a geomembrane sloping wall

Fig.1 Maximum cross section of the cofferdams with two different seepage-proof structures for seepage analysis

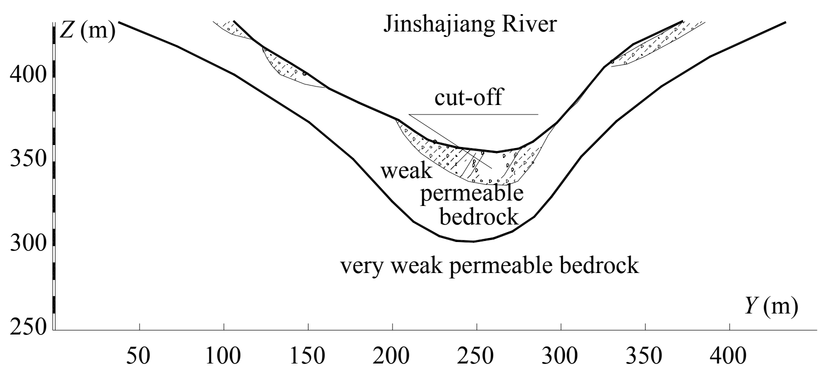


Fig.2 Geological longitudinal section of cofferdam for analysis

Three main seepage problems are paid attention to in the design and comparison of the two seepage-proof styles of the cofferdam: 1) the seepage discharge is small enough to accepted; 2) the seepage stability is ensured; and 3) the seepage discharge and stability is accepted even if under the abnormal condition such as a small crack in the cut-off due to the construction or other reasons. As a result, a three-dimension seepage analysis is used to investigate the seepage behavior of the cofferdam. Two operating conditions for the cofferdam are considered in the analysis: 1) normal conditions where no cracks occur in the seepage-proof structure; 2) abnormal conditions where some cracks occur in the seepage-proof structure. The possible highest upstream water level is considered in the two cases.

There are two main challenges in the seepage analysis: one is the remarkable difference among permeability of the fill materials, which has great effects on the stability of iteration computation of the free surface; the other is the simulation of the cracks, which is too thin (about 10 cm). The dimensions of FEM mesh therefore range from very small (to simulate the cracks) to large (to simulate the cofferdam body). Presented in this paper is a brief introduction of three-dimensional FEM analysis of the seepage behavior of the Xiluodu upstream cofferdam for the two different design schemes.

NUMERICAL MODEL

Permeability of fill materials

The structures of two seepage-proof styles are shown in Fig. 1 where the system of coordinate is taken for convenience of the analysis. The x-axis is the direction of the longitudinal axis of the cofferdam; the y-axis, the direction of flow; the z-axis, the direction along the elevation. The corresponding coefficients of permeability and legends of material zones are listed in Table 1.

Table 1. Legends and corresponding coefficients of permeability of main material zones

Material zone	Legend (Meterial Number)	Permeability coefficient cm/s
Very weak permeable bedrock	1	5×10^{-5}
Weakly permeable bedrock	2	5×10^{-4}
Overlying stratum	3	0.1
Concrete cut-off	4	5×10^{-7}
soilaggregate	5	2×10^{-5}
Geomembrane	6	10^{-11}
Transition zone	7	0.03
Rockfill	8	0.1

Principle and boundary conditions

Steady seepage flow in saturated and unsaturated soils may be described by the following three-dimensional differential equation:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial H}{\partial z}\right)=0 \qquad (1)$$

in which H is the water head; k_x, k_y, k_z are respectively the coefficient of permeability in the three directions of x, y and z-axis, which can be written as

$$k_i=(k_0)_i k_r \qquad i=x,y,z \qquad (2)$$

where $(k_0)_i$ is the coefficient of permeability in the three directions for saturated soil, and its magnitude mainly depends on the characteristics of soil; k_r is the relative coefficient of permeability, which is a function of pore pressure and water content of soil.

The boundary conditions used in the analysis are given as follows.

1) A constant water head H is taken or

$$H=H_0 \qquad (3)$$

2) At the impermeable boundary,

$$\partial H/\partial n=0 \qquad (4)$$

3) At the steady free surface,

$$H(x,y,z)=z(x,y) \qquad (5)$$

where n is the direction normal to the boundary.

In the seepage analysis, two conditions must be satisfied simultaneously on the free surface boundary: one is that no flow crosses the boundary; the other is that the pressure is atmospheric (Eq. 5). In this paper, a technique is adopted to obtain the free surface. In the free surface, impermeable boundary condition is discarded. The region of unsaturated soil is covered in the solution and the free surface is the surface that the pore pressure is zero, which can be determined with interpolation (Jiang CB & Du LH, 1999). A fixed-mesh seepage FEM thus is derived, by which the calculation is simplified and consequently the seepage behavior of the cofferdam could be examined in more detail.

Numerical Modeling

As shown in Fig. 1 and Table 1, the routes of seepage through the dam body and overlying stratum are cut off by a soilaggregate sloping core wall (or a geomembrane sloping wall) and concrete cut-off wall. The weak permeable bedrock becomes the main routes of seepage. Therefore, the bedrock should be well simulated in the seepage analysis. The mesh covers a certain area of very weak permeable bedrock in the foundation so that the boundary could be considered impermeable.

According to the specific design flood probability and construction requirements, upstream and downstream water levels of 434.1m and 330m are taken in the seepage analysis.

Geomembrane is too thin (no more than 1mm) to form the FEM mesh suitably. In addition, the holes in the geomembrane, which may be induced during construction, also need to be considered. An equivalent element is adopted as a treatment of simplification, i.e., the thickness of each element of the geomembrane is magnified and the coefficient of permeability is equivalently enlarged. In the analysis, the thickness of the element is set to 1m and the coefficient of permeability is accordingly taken 10^{-7} cm/s.

Special attention in the analysis of the abnormal conditions is paid to the following four types of cracks that may occur in the seepage-proof structure: (1) A horizontal crack 30m long and 10cm wide along the joint between the concrete cut-off wall and soilaggregate (or geomembrane) wall; (2) A horizontal crack 30m long and 10cm wide along the joint between the concrete cut-off wall and bedrock; (3) Two different vertical slots 20cm and 40cm wide in the concrete cut-off wall along the depth of the whole overlying stratum (about 340m-360m level); (4) For the cofferdam with a geomembrane sloping wall, a slot 30m long and 10cm wide is considered in the geomembrane. To evaluate conservatively, the cracks are all considered to appear in the maximum cross section.

The cracks are simulated by a series of thin elements. The mesh near the crack is densified and added with a proper transition. The 3D seepage behavior caused by cracks and bedrock can be both properly considered at the same time.

Fig.3 shows an overview of 3D FEM mesh for seepage analysis, which has a total of more than 8000 nodes and elements.

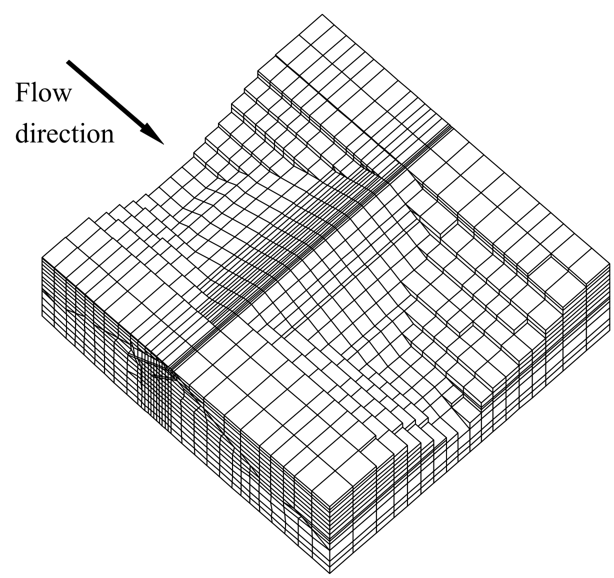
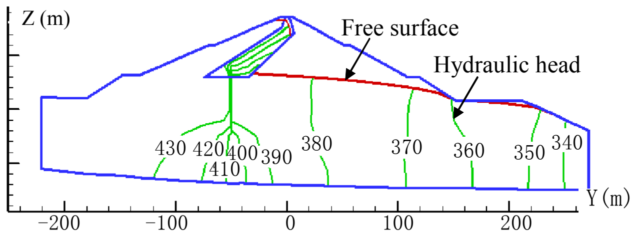


Fig.3 An overview of FEM mesh

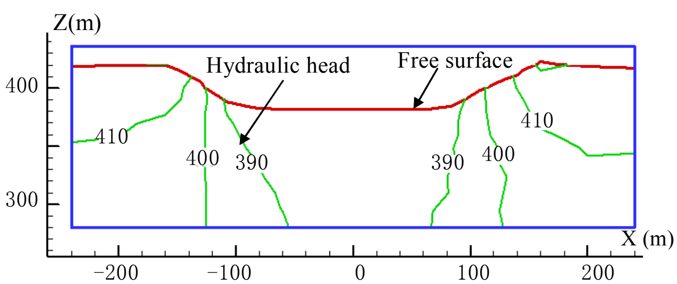
RESULTS OF NORMAL CONDITIONS

The discharge of seepage and distribution of water head (*H*) are obtained for the two different design schemes. The maximum discharge of seepage is 0.29m^3/s for the soilaggregate sloping core wall, less than 0.46m^3/s for the geomembrane sloping wall. It is preliminary concluded that the two seepage-proof structures are both acceptable because the seepage discharge of the two are not large. The curtain wall is not necessarily built in the bed rock as a suggestion.

Figs. 4 and 5 show the distribution of the water head in the maximum cross section and along the maximum longitudinal direction for two design schemes with different seepage-proof structures. The seepage takes place mainly in the weak permeable bedrock. As shown in Figs 4b and 5b, the flow in the middle part is supplied through the bedrock near two shoulders of the dam, so that the free surface is curved in the maximum longitudinal section. The geomembrane sloping wall is much thinner than soilaggregate sloping core wall, the by-pass seepage of the sloping wall through the bedrock becomes much prominent than that of the sloping core wall. That is an important reason why the discharge of seepage and position of the free surface for the cofferdam with a soilaggregate sloping core wall are lower than those for the cofferdam with a geomembrane sloping wall.

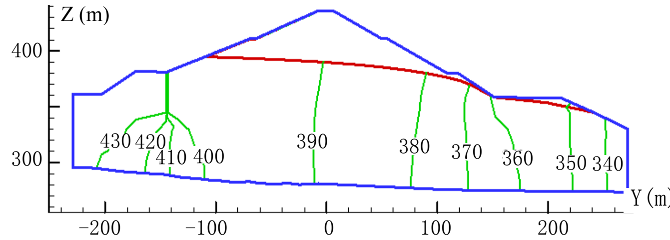


a) Maximum cross section

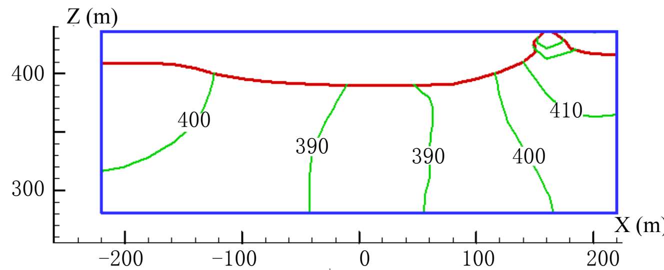


b) Maximum longitudinal section

Fig. 4. Distribution of water head and position of free surface for cofferdam with a soilaggregate sloping core wall



a) Maximum cross section



b) Maximum longitudinal section

Fig. 5. Distribution of water head and position of free surface for cofferdam with a geomembrane sloping wall

RESULTS OF ABNORMAL CONDITIONS

<u>Flow field analysis</u>

It is found that the discharge of seepage rises significantly when the cracks take place in the seepage-proof structures. As an example, the effect of the vertical slot 20cm wide in the cut-off wall is here discussed in detail. For the cofferdam with a soilaggregate sloping core wall, the discharge of seepage increases up to 0.52m^3/s from 0.29m^3/s of the normal condition. For the cofferdam with a geomembrane sloping wall, the discharge of seepage increases up to 0.69m^3/s from 0.46m^3/s. The flow field in the cofferdam is also affected considerably by the cracks, especially near the cracks. As an example, Figs 6 and 7 show the whole flow field and distribution of local water head near the crack for the cofferdam with a soilaggregate sloping core wall. It can be seen that the crack takes place in the overall part of the cut-off wall in the overlying stratum (340m to 360m level). Comparing with the normal condition, the free surface raises and the contours of the water head become dense near the crack. However, the flow field tends to become consistent with that of normal condition in the space at a little distance away from the crack. It indicates that the crack has a much great influence on the flow field near the crack, but its effect is limited in a not big local space.

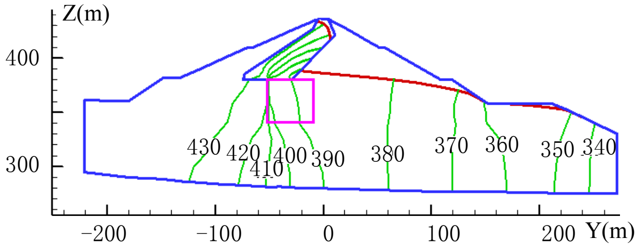
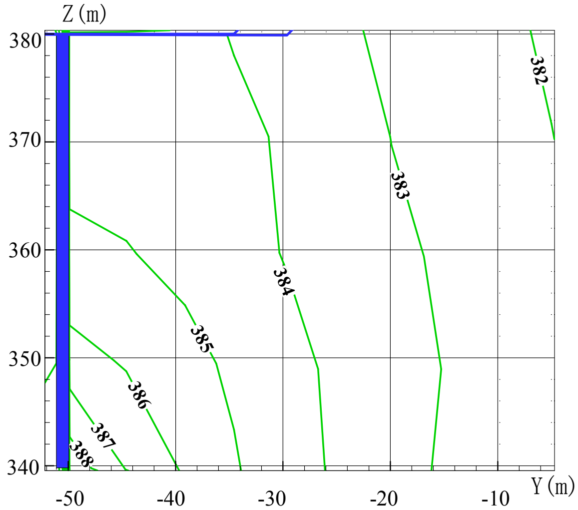
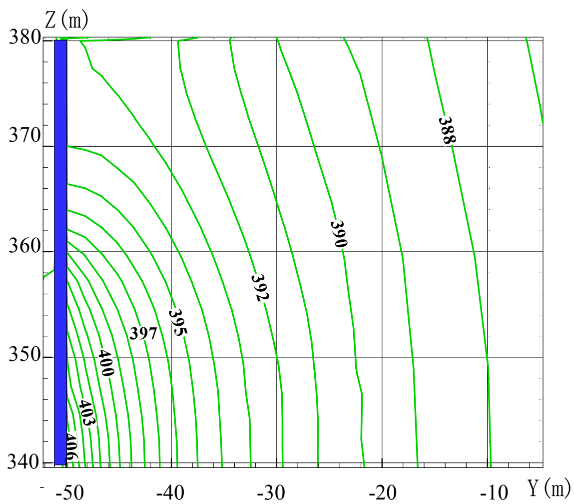


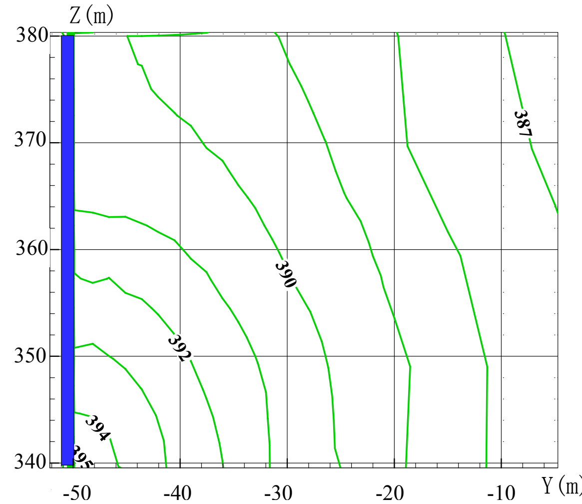
Fig. 6. Distribution of water head and position of free surface in maximum cross section for cofferdam with a soilaggregate sloping core wall and a vertical slot with 20cm wide in cut-off wall



a) A locally enlarged zone of maximum cross section for normal conditions



b) Local cross section through the center of a vertical crack



c) Local cross section at a horizontal distance of 20m away from the crack

Fig. 7. Distribution of water head in the locally enlarged zone shown in Fig. 6 with the rectangular window

<u>Seepage stability analysis</u>

As seen from the Figs 6 and 7, big gradients of seepage are induced in the local space near the crack. As a result, the stability of seepage needs to be evaluated in the design of the project.

Two basic factors are determined from the seepage stability analysis: 1) actual gradient of seepage and its distribution in the seepage field; 2) allowable gradients of seepage, depending on the fill materials and bedrocks. For this project, the seepage stability of seepage-proof structure and bedrock do not need to be considered. The allowable seepage gradient of the overlying stratum and gravel is taken 0.2 conservatively. The cofferdam is regarded in state of seepage stability if there is not a very big space in the overlying stratum where the actual gradient of seepage is more than the allowable gradient of seepage. The average gradient in a certain space near the crack is usually applied in practical engineering. The average gradient, however, is not easy to be determined reasonably, especially for such a 3D condition. A new concept called critical gradient zone, therefore, is proposed to evaluate the seepage stability of the cofferdam. The critical gradient zone indicates a closed zone enveloped by the contour with a constant allowable seepage gradient of 0.2, the downstream side of the cutoff wall and the bedrock surface. It is shown with the shaded region in Fig. 8. The actual gradient of seepage in the zone is more than the allowable gradient of seepage. The size and shape of the critical gradient zone show a risk level of the dam again the seepage failure.

Fig. 8 shows an example showing the critical gradient zone for the cofferdam with a soilaggregate sloping core wall and a vertical slot with 20cm wide in the cut-off wall. Similar phenomenon can also be seen in the cases with the other different cracks. The critical gradient zone almost vanishes in the space 20m away from the crack and is limited in the overlying stratum only. Based on the present results and other engineering experience, the whole seepage stability of the Xiluodu cofferdam is adjusted to be assured.

CONCLUSIONS

A 3D fixed-mesh FEM is used in the seepage analysis for the upstream cofferdam of the Xiluodu hydraulic power station. The method is confirmed effective and feasible by good regularity of the results. The abnormal conditions considering cracks that may occur in the cut-off wall are involved in the analysis. To evaluate the seepage stability of the cofferdam, a new concept called critical gradient zone is introduced. The following conclusions can be obtained based on the results of analysis.

1) The fixed-mesh FEM used in the present analysis is valid for the complicated structure with great difference in the permeability of materials of different zone.

2) For the normal conditions, two seepage-proof structures, including a soilaggregate sloping core wall and a geomembrane sloping wall, are both effective. The soilaggregate sloping core wall is relatively better.

3) For the abnormal conditions, the discharge of seepage increases significantly when a crack takes place in the cut-off wall for both design schemes with the two different seepage-proof structures. The crack of the cut-off has a great influence on the flow field near the crack, but its effect is limited in a not big local space. The critical gradient zone may appear in the overlying stratum behind the cut-off wall, but it vanishes 20m away from the crack.

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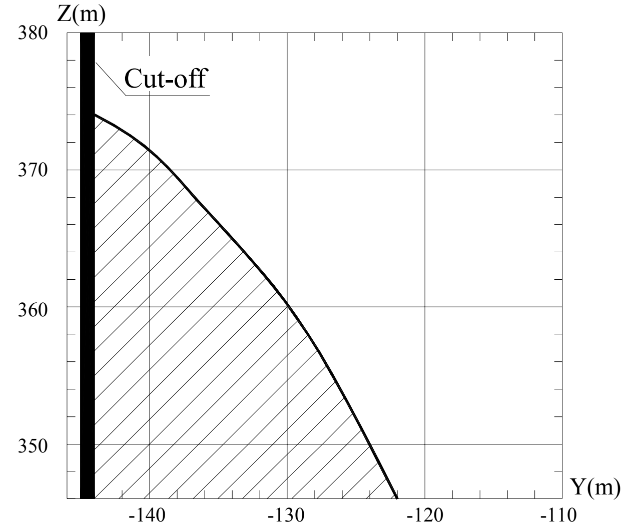
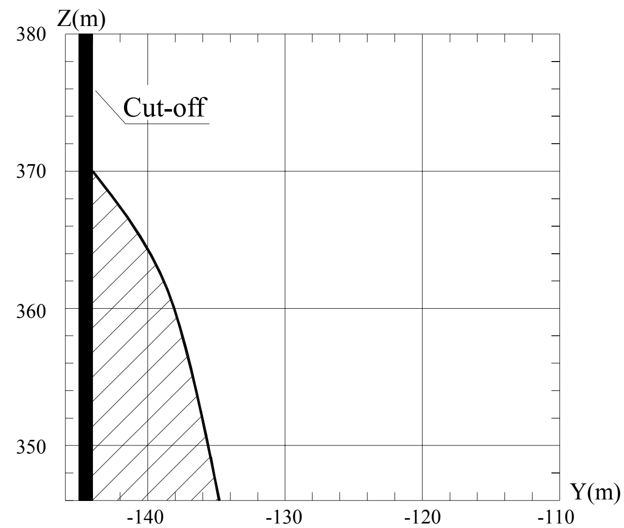
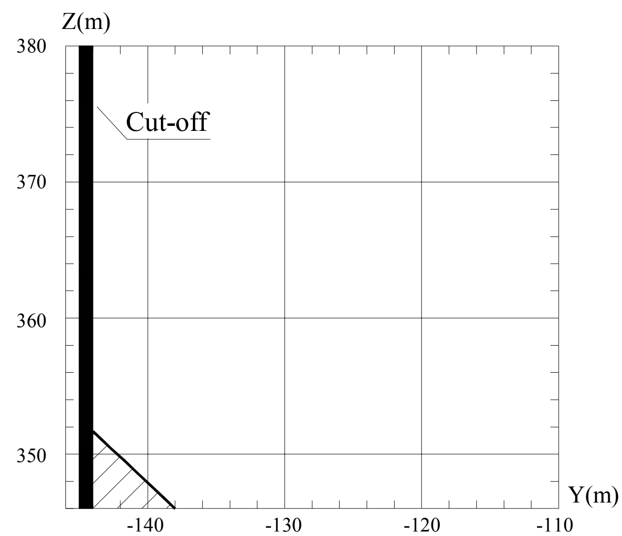


a) Local cross section through the center of crack



b) Local cross section at a distance of 10m away from the crack



c) Local cross section at a distance of 20m away from the crack

Fig. 8. Critical gradient zone (in a locally enlarged zone of Fig. 6 shown with the rectanger window) for cofferdam with a soilaggregate sloping core and a vertical slot 20cm wide in cut-off wall