International Geotechnical Symposium on Theory and Practice of Earth Reinforcement / Fukuoka Japan / 5-7 October 1988
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Study on the effect of the vertical RC bolting on the unstable slope

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ABSTRACT: This paper describes the outcome of the research on effects of the vertical RC bolts on unstable slopes. Herein, the concept and case studies on vertical RC bolting are introduced, and its effectiveness is evaluated based on field survey results.

1. PREFACE

In the past, the tunnelling, using timber to support tunnels, was considered uneconomical in many uneasy works to be safely operated. The machines and materials to be used had not been sufficiently developed, so a great deal of time and labor was required to complete the works. Tunnel routes were chosen which would minimize the tunnel length, where the geological condition would be easy to excavate. However, tunnelling technology has made rapid progress in recent years, and it is now generally recognized that it is possible to construct tunnels with high safety and at low cost. Two particularly important breakthroughs which have deepened that impression were the introduction of the New Austrian Tunnelling Method (NATM), now the standard tunnelling technique in Japan, and the reflection of results of simulation performed beforehand by the numerical analysis etc. to the design and the execution of tunnels. In addition, the roles of tunnels, with the progress of urbanization and high density land use, have been increasingly growing. Faced with this social necessity, many tunnels nowadays have to be constructed in places with less favorable conditions. It is expected that this tendency will continue.

The key issue in the excavation of tunnels is the stability of the face.

The primary factors which determine this stability can be summarized as follows:

1. the strength of the natural ground
2. the shape and size of the tunnel
3. the initial stress condition of the natural ground
4. the excavation speed, etc.

Geological factors have a particularly important influence.

In poor ground, an auxiliary method must be found to strengthen the stability of the face. The aim of an auxiliary method is to reinforce the ground in front of the face to make it possible for tunnelling. The auxiliary method can be classified broadly into two categories, whether it can be performed by using the facilities and machines already existed in the field or not. The first, including the forepiling, facepiling etc., can be adopted easily and helpful to maintain the face stability until the support system has installed completely. The second, including well point drainage, deep well,grouting, artificial ground freezing, and the vertical RC bolting method etc., must use the new facilities and machines, and is applied to improve the ground condition.

It used to be common to consider the design of tunnnels simply as a problem of earth pressure, Terzaghi's theory of loosening pressure being the typical example. Recently, however, more emphasis has been placed on deformation, applying NATM measuring or the numerical analysis method. Accordingly, the three-dimensional effects of tunnelling have come into focus, and the hitherto somewhat neglected behaviour of the natural ground beyond the face has been given more attention in the design and execution of tunnels.

The results of NATM measurement and three-dimensional FEM analysis have shown that looseness equivalent to at least one-third of the total displacement at the time of convergence has already occurred in the natural ground in the neighborhood of the face while the face is approaching. These pre-displacements or looseness reduce the stability of the face. The "vertical reinforced concrete bolting method" is an auxiliary technique which has been developed to control this looseness and raise the stability of the face or slope.

Briefly, the method is to drive fixed pitch mortar reinforced concrete piles into holes bored from the surface.

In this report, we present actual results detailing the effectiveness of the vertical reinforced concrete bolting method, our view of this method and a case study.

2. THE VERTICAL REINFORCED CONCRETE BOLTING METHOD

The vertical reinforced concrete bolting method is construction technique for maintaining the stability of the natural ground, either temporarily or in the long term, by reinforcing against the dislocations caused by the approach of a tunnel.

This method is applied in places where the geological conditions are extremely unsuitable for tunnel construction, such as talus layers in the neighborhood of portals or soft ground.

The vertical reinforced concrete bolting is normally executed by inserting bolts (ϕ some 30mm) into boring holes (ϕ some 100-120mm) filled with mortar.

The method:

1. improves the stability at the face,
2. has a suspension effect,
3. improves the stability of the slope,

and so on.

2.1 Rise in stability at the face

The most important point when excavating tunnels is to stabilize the face. Fig.1 shows a face reinforced by vertical reinforced concrete bolting. As Fig.1(a) shows, collapse of the face would usually occur in almost all cases when slippage happens toward the area in front of the face.

By driving in mortar reinforced concrete piles, we raise the shear strength of the natural ground to prevent rupture of the natural ground; and thus, the natural ground in front of the face is stabilized. This method also holds together discontinuous areas of natural ground composed of joints and fissures etc., preventing the rock mass from forming blocks, and the weakened rock mass from segregating and falling off.

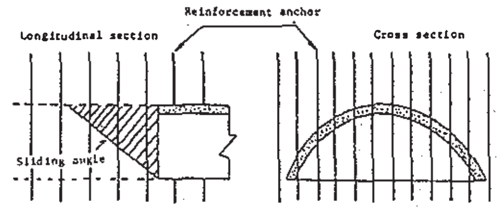

Fig.1 Reinforcement of Face

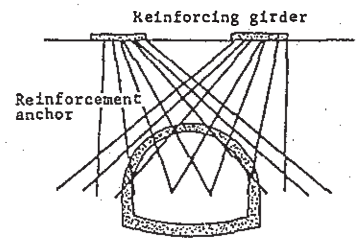

Fig.2 Reinforcing method by suspension effect

2.2 Suspension effect

When overburden is small, the ground pressure can be reduced by suspending the ground on bolts fixed to beams laid on the surface. This supplements the natural supporting ability of the ground.

2.3 Rise in stability of the slope

When we look at the topography and geology in the neighborhood of the entrance to a tunnel, we often find that there are several layers of weathering on the bedrock and a talus layer covers the top. There is a high possibility of slope collapse or landslides when excavating tunnels under these conditions.

We can raise the stability of a slope by driving in bolts to hold together discontinuous layers and rock mass that are apt to cause slope sliding.

It is supposed that none of these results are obtained individually, but that there is interaction among them.

3. A CONCEPTION OF THE DESIGN FOR VERTICAL REINFORCED CONCRETE BOLTING

The basic conception of the design for vertical reinforced concrete bolting is to raise the inherent shear strength of the natural ground by driving mortar reinforced concrete piles into the ground.

The force needed to prevent deformation of the natural ground by the excavation is borne by the piles, utilizing the adhesive power of the mortar.

The mortar and bolts both serve an important function in restraining the deformation of the natural ground.

In sediment or weathering layers broken into flinders, the mortar permeates the soil or cracks to form cylindrical clods around the RC bolts, raising the cohesion or angle of internal friction of the natural ground. The shear and bending strength of the piles resists the sliding force which occurs at contact surfaces of sediment and rock or between rock layers.

The sizes and intervals of the borings and the thickness and length of the bolts are mostly calculated according to the physical properties of the natural ground. In this case, we include the following two considerations:

1. The axial intervals of the tunnel should roughly correspond to the intervals of the steel arched supports. Intervals at right angles to the face should be chosen by the size of the boring, and the dimensions of the bolts. The earth pressure at the face depends upon the quantity of earth between each bolt interval.
2. The choice of procedure must depend on the availability of machines and the suitability of the ground.

4. CASE STUDY OF VERTICAL REINFORCED CONCRETE BOLTING (Example of the 2nd Shirasaka Tunnel at Yodogasawa)

The examples of the vertical RC bolting adopted in the past is shown in Table 1. Here, we describe a case study at Yodogasawa, the 2nd Shirasaka Tunnel of Shinonoi Line, where the tunnel was constructed under an unstable slope.

4.1 Outline

The 2nd Shirasaka Tunnel of the Shinonoi Line of Japan Railways is a 1765m double track tunnel ($A=65m^2$), situated almost in the center of Japan. About 800m from the Shiojiri-side portal, there is a marshland called Yodogasawa, and in one place where the minimum thickness of the ground above the tunnel would be only about 1m. Landslides have happened here several times in

Table 1 Examples of vertical RC Bolting

Execution	Pile diameter (mm)	Pile length (m)	Quantity
Rout 373 Shidosaka Tunnel	76.0 100.0	5.65 (average)	235
Misawagawa water branch tunnel	300.0	8.8-9.6	214
Minamihonjyuku manhole	116.0	12.5	195
Uchiumi Tunnel Rout 220, Miyazaki	101.0	4.1-9.6	208
Toi sewage tunnel	100.0	8.0-14.0	123
JR Second Shirasaka Tunnel	116.0	8.0-20.0	745
JR Kyobashi Tunnel	100.0	20.0-26.0	489

the past, and the topographic and geological conditions suggested that a landslide might be induced by tunnel excavation. Further, it appeared that it might be difficult to secure the stability of the tunnel. Therefore, it was decided to reinforce the stability of the natural ground by vertical reinforced concrete bolting. Execution of the tunnel was carried out under the NATM, with a conventional method adopted at the place where the covering was very thin.

The geology here consists of lower layers of Cenozoic Neocene Miocene Japanese red pine alternation with a high proportion of sandstone and sandy mudstone, mudstone alternation.

The spot where the tunnel was to cross the Yodogasawa Marshland is some 15m wide, at a point where both banks form oblique slopes of 35°. In the neighborhood of Yodogasawa, deposits of the present riverbed had accumulated to a thickness of 4 to 5 meters, and they were supposed to appear in the upper half of the tunnel's section.

4.2 Vertical reinforced concrete bolting

The vertical reinforced concrete bolting was executed over the area shown in Fig. 3.

The mean value of physical properties of the mudstone is shown in Table 2. The bolting zone was positioned in a sphere where a covering was thicker than the calculated Terzaghi's height of loosening bedrock; namely the earth covering thickness of 1.5D from the crown of the tunnel (D: diameter of tunnel).

The pitches of the reinforced concrete bolts were decided according to the equilibrium of the slope, a virtual sliding surface being imagined. Calculations on the assumption that the mortar reinforced concrete bolts might provide shear-resistance against the sliding force showed that it was proper to drive in piles every $1.5m^2$.

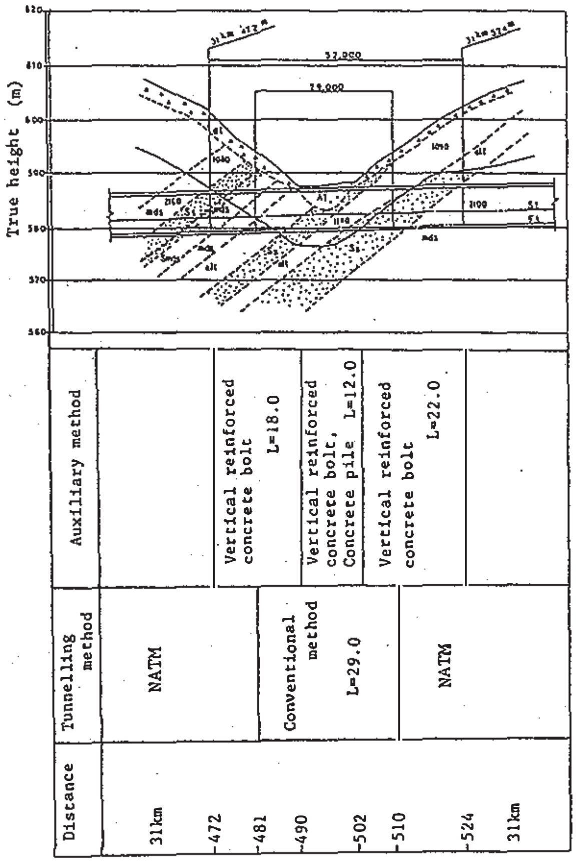

Fig.3 Outline of RC Bolting Zone

Table 2 Physical Properties Value of Mudstone(average)

Unit weight (kgf/cm^2)	Unconfined compression strength(t/m^3)	Angle of internal friction (°)	Cohesion (kg/cm^2)
1.8	50	30	2

4.3 Measurement

Measurements were made to precisely ascertain the behavior of the natural ground to confirm the effects of the vertical reinforced concrete bolting, and, at the same time, to secure the safe execution of the tunnel excavation by rapidly feeding back the results of the measurements. Each measurement is given below for 31km 476m.

1. Surface subsidence
Surface subsidence was measured by establishing five survey stations at 10m intervals in the direction of the tunnel's length and also five stations in the crosswise direction.

A diagram of surface change over time is shown in Fig.4. Movement of the surface began when the face came to the point at - 0.5D (D: diameter of tunnel) and, when passing the upper half of the face, it reached 50% of the total subsidence.

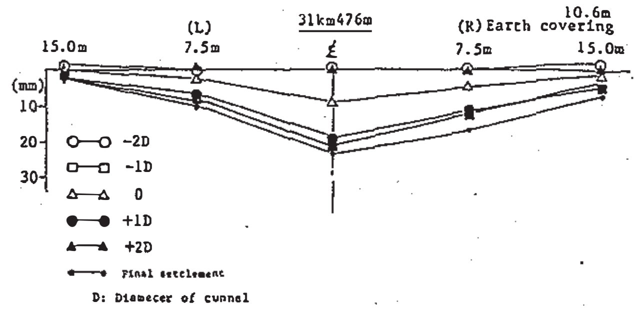

Fig.4 Diagram for Change of Ground Surface Subsidence by Time Lapse (Tunnel cross-section)

2. Ground horizontal displacement
Measuring instruments were set up on either side of the tunnel, 9 meters away from the tunnel. Ground horizontal displacement volume and direction are shown in Fig.5. The left side instrument showed a movement in the axial direction of the tunnel, namely a movement along the slope with displacement especially notable at the talus part (GL-8m). By contrast on the right, the upper layer revealed prominent displacement in the axial direction,

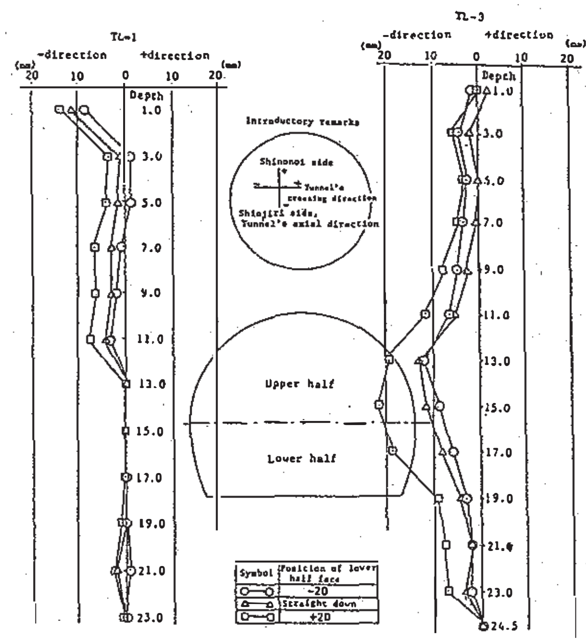

Fig.5 Ground Horizontal Displacement (Tunnel crosswise direction) Displacement by Lapse of time as lower half face advances

and the lower layer prominent displacement in the crosswise direction, these two layers being in the environs of the crown of the tunnel. These results showed that the surface talus layer was greatly influenced by the slant of the slope and, in the environs of the crown of the tunnel, a relatively greater side pressure was imposed from the right side as a result of the release of stress during the excavation.

3. Ground vertical displacement

Ground surface subsidence was more marked on the right side, centering on GL-14m. The relative degree of displacement shifted from the compressed side to loose side between GL8 and 10m before and after passing the upper half, with a loose layer apparently existing between them. A distribution diagram of strain caused by ground subsidence, classified by depth, is shown in Fig.6.

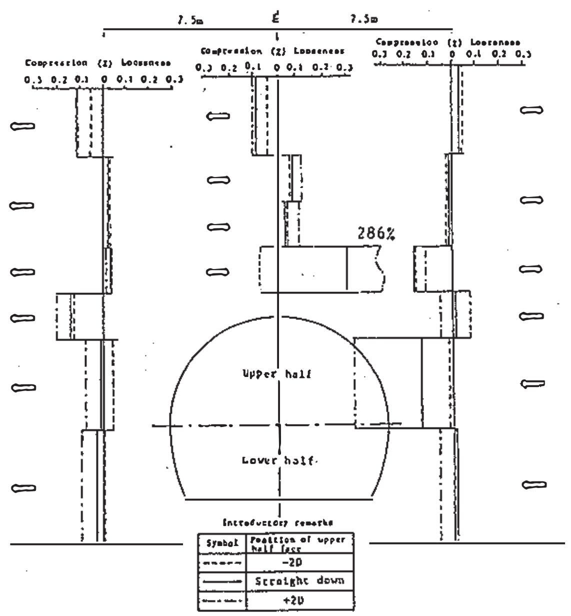

Fig.6 Strain Distribution Diagram by Ground Depth (Survey point 31km476m)

4.4 Behavior of the natural ground at Yodogasawa

1. Movement in the axial direction of the tunnel

When the upper half face arrived in front of the vicinity of the crown of the tunnel, the axial force of the bolt and ground displacement began to change. Ground surface subsidence showed little movement before the upper half face reached -0.5D. The stages at which each measurement point was first influenced by the tunnel face are shown in Fig.7 . From this, it was found that the straight line distance at which the influence began to be felt was 10.5 to 11.0m. The influence of the tunnel excavation seemed to spread in concentric circles from the crown of the tunnel face. Pre-displacement, (as a ratio of the measured value at the time the face arrives to the final measurement) was some 40 to 55%.

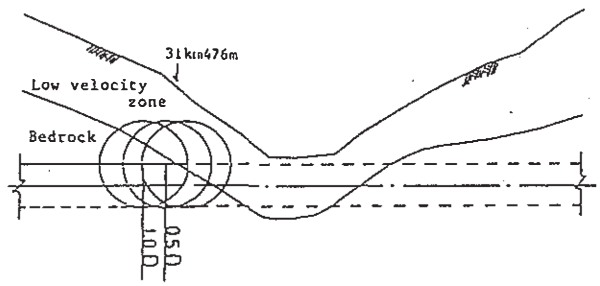

Fig.7 Sphere Affected by Excavation

Comparing the crown subsidence quantity at the time of the upper half excavation with that at the time of the lower half excavation, we found a ratio of subsidence quantity of almost 1:1. The quantity of the crown subsidence increased under the influence of the lower half excavation in the same way as during the upper half excavation. However, the subsidence of the ground surface showed only a slight increase, with little influence from the lower half excavation. In addition, when measuring the axial force on the reinforced concrete bolts driven into the central axis of the tunnel, we found little change caused by the approach of the lower half face. It was concluded that the reinforced concrete bolts seemed to restrict the displacement of the natural ground as predicted.

2. Movement in the crosswise direction

The inclinometer installed at equal distance from the tunnel center showed movement along the slope in the vicinities of the ground surface and the tunnel. There was a tendency for the side pressure to act from right to left.

The ground strain distribution diagram showed looseness some 7m away from the surface of the tunnel wall and compression on the upper parts. Regarding axial force distribution, a tensile force was felt some 7m away from the surface of the tunnel wall. Thus, the two results coincided exactly. The earth covering at this spot was some 1.0D, with the ground configuration of a slope. Judging from these conditions, it had been supposed that the formation of a ground arch would be difficult during tunnel excavation. However, the measurements showed that a ground arch had been formed.

The reinforced concrete bolts can be said to have formed a ground arch and stabilized the ground surface in a geologically difficult site.

5. EFFECTS OF THE VERTICAL REINFORCED CONCRETE BOLTING

It was clear that the vertical reinforced concrete bolting successfully restrained the displacement of the natural ground and controlled the increase in displacement quantity. The working effects can be divided broadly into the following two categories:

1. Controlling the quantity of subsidence at the upper part of the tunnel
2. Controlling the influence of the excavation on the front of the face

5.1 Effects of restraint on subsidence quantity at the upper part of a tunnel

In the case of the 2nd Shirasaka Tunnel, the influence of the tunnel excavation spread in concentric circles from the top of the face. This had already reached to the ground surface when the upper half face arrived. Accordingly, the natural ground on the upper part of the tunnel began to subside, but this subsidence was restrained in the vicinity of the reinforced concrete bolts. It is evident from the axial force distribution on the bolts that the restraint on subsidence was the result of frictional force on the surface of the bolts. It has been found that when driving reinforcements, such as rock-bolts or reinforced concrete bolts, into natural ground, both the yield load of the natural ground and the residual stress after yielding increase. The absorption energy also increases prior to the breaking of the natural ground. There are two ways of viewing these phenomena. One is to approach them from a macro-viewpoint, in which the physical properties of the whole natural ground, including those of the reinforced concrete bolts, are supposed to be improved, while the other is to view them in terms of the so-called suspension and reinforcement effects.

Restraining of subsidence by reinforced concrete bolts is supposed to be achieved by the reinforcement effect to make the natural ground in the triaxial stress state and by the suspension effect to restrain the natural ground.

5.2 Restraint of the influence of excavation on the front of the face

It was made clear by the results of measurement and analysis that the influence on the front of the face was large, especially at places like Yodogasawa where the diagonal movement (tunnel axial direction) is great. However, judging from the fact that the influence of excavation beneath this slope was in fact almost equal to that of tunnel excavation beneath a flat surface, the influence on the upper part of the tunnel and on an oblique front could be restrained by some working. This was the restraint obtained by the vertical reinforced concrete bolting method.

These effects are supposed to have been produced by the facts that the bearing force against exterior load increases with the restraint imposed on the ground by the reinforced concrete bolts, and stability of the natural ground rises accordingly. At the same time, the extent of the influence of the excavation is supposed to become narrower, because the value of the apparent modulus of elasticity rises and the resultant strain becomes less.

6. POSTSCRIPT

The vertical reinforced concrete bolting method, developed at the same time as NATM was introduced into our country, has often been used with perfect success and has become commonly known as an excellent auxiliary method for construction.

Hereafter, tunnels will be built in increasingly difficult conditions. Under these circumstances, the role the vertical reinforced concrete bolting method will be quite important as a means for executing economical tunnel construction. The success of this method is achived after first confirming the stability of the natural ground, and then by application in conformity with a precise estimate of the behavior of the natural ground, using cumulated data and careful construction techniques.

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