PART TWO

Tunnel collapses in swelling clay zones

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Part 1 of this article (Nov '89) gave some examples of the collapse of tunnels in swelling clay gouges. Many of the collapses were caused by insufficient rock support as a result of underestimating the high loads exerted by the swelling process. When swelling zones are present in a tunnel it is essential that a method for detecting their occurrence, together with calculations of appropriate rock support, be established. Part 2 shows how careful site description and laboratory investigations of the material with swelling properties can be used to calculate the maximum swelling pressure to be accommodated in the design of the required rock support.

The aim of laboratory investigations of swelling clays is to measure the most important clay properties required for calculations of the swelling loads whereby methods of rock support can be determined. The presence and types of swelling clay minerals can be found from X-ray and Differential Thermal Analysis (DTA) analyses. However, neither of these methods gives an indication of the swelling pressure that can be exerted. They can therefore only be used in qualitative description of the gouge material.

Swelling properties are usually measured by oedometer tests. They used to be carried out as qualitative analysis based on results from earlier experience. Today, a method using a laboratory procedure that corresponds to the conditions in a tunnel is under development. It therefore reduces the need for estimating the various factors acting during the swelling process. The method requires, however, that the site is properly described with respect to structure, orientation and thickness of the weakness zone(s), together with total thickness of the clay-containing parts. As described later the method is of particular importance when shotcrete is used as support.

Clay zones are mostly composed of secondary minerals and of a mixture of rock fragments ranging in size down to clay particles. The zones encountered in Norway are believed to have been formed and developed under the special geological conditions of stresses and heat existing in the Earth's crust. The particles in such zones are therefore shaped and well adapted to each other under high stress conditions. Because of this the texture of these 'loose' materials is more like that of rock than soil.

Since undisturbed, in-situ samples of a clay zone can seldom be obtained, it is necessary to use a procedure which includes the main properties of the swelling material. The swelling tests are therefore carried out on elutriated and dried samples with particle size less than 20 microns. This grain fraction will contain almost all the swelling minerals because the larger grains will disintegrate during rough treatment of the sample material. Twenty grams of dry sample powder is loaded at 4MPa in the oedometer before it is given access to water through the lower filter (Fig 1). After all the material in the sample has finished swelling at this pressure, the thickness of the sample is recorded. A step by step release of the sample is then carried out to best imitate the in-situ conditions in a tunnel.

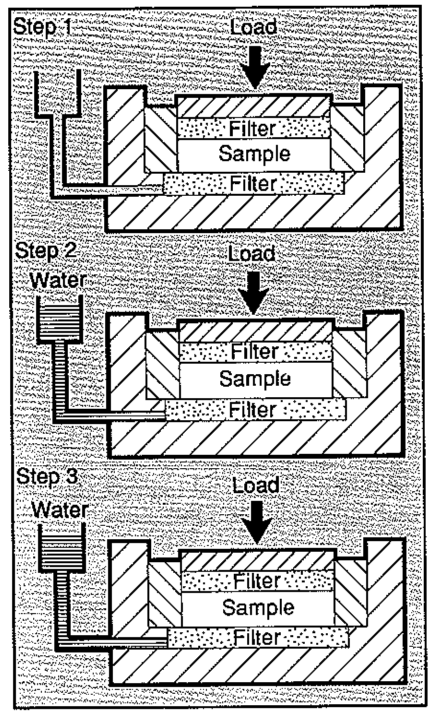

Fig 1. Principle of oedometer test for measuring the maximum swelling pressure of gouge materials.

Swelling curve

In spite of careful preparation of the sample, an artificially larger, elastic deformation than in undisturbed, in-situ samples will occur during the release of pressure. This pure elastic contribution can be compensated for by subtracting a 'standard' elastic deformation curve from the curve measured for the swelling clay. The 'standard' curve is found from equivalent tests on other gouge materials free from swelling minerals. They show variations down to a load step of 1MPa. Fig 2 shows an example of a swelling curve found in an oedometer test and the subtraction of a 'standard' curve to give the resulting swelling curve.

Both physiochemical (swelling) and elastic forces are accumulated in the clay sample before unloading. The elastic forces decrease rapidly during unloading, while the mobilisation of the swelling forces requires, in addition to water, an increasing volume during unloading. The swelling forces will therefore give the dominating contribution to the pressure curve after initial volume increase. This causes the resulting swelling curve to show a peak after a small volume increase, which is the maximum swelling pressure for the sample for the consolidation chosen.

Testing shows that maximum swelling forces increase linearly with the (pre) consolidation pressure, at least up to 8MPa. At higher consolidation, the swelling forces in samples with very high content of smectite increase somewhat less. As shown in Fig 2, the pressure is strongly reduced if a small deformation or volume increase is allowed in addition to time for release of elastic forces.

Most of the radial, elastic deformation in a swelling zone generally takes place before even quickly installed rock support can be applied at the tunnel face. The radial swelling pressure may, however, act on the support while the swelling decreases with increasing pressure depending on the shear strength of the material and the 'silo effects' in the zone.

One practical consequence of this is that the amount of rock support in a tunnel can be reduced if some space for

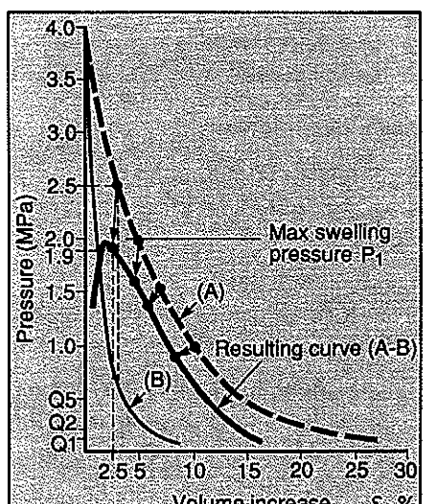

Fig 2. Swelling curves measured for samples of (a) swelling clay and (b) non-swelling materials. The representative swelling curve used in the calculations of support is found as the difference between the two curves.

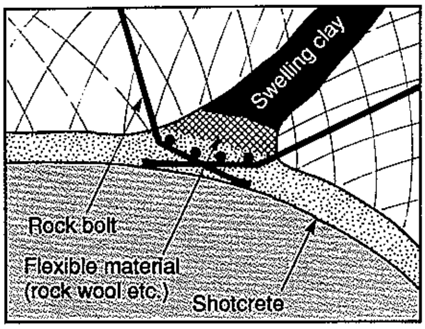

Fig 3. Method of sealing of smaller swelling zones using shotcrete.

volume increase is introduced between the support and the zone to be supported. This is in fact what takes place when cast in place concrete linings are applied as rock support. There will always be a gap in the roof between the concrete and the rock where an expansion of the swelling clay can take place. Shotcrete applied at the face gives no such space or time for initial swelling. A way of introducing the necessary space when shotcrete is applied is to cover the zone with some type of compressible material before shotcreting (Fig 3).

Another practical implementation of the swelling tests is the ability to predict the maximum swelling pressure on the support, as further described in the next section.

Rock support of swelling zones

Evaluation of support requirements needs a knowledge of both the loads acting on the support and the load carrying capacity of the support itself. The loads from swelling clay zones are often difficult to assess exactly because of the many factors involved. Evaluations must therefore be based on simplifications dealing with only the most important factors. Some preliminary results from a system under development show how calculations of the maximum swelling pressures can be made are given below.

The load from a swelling zone on the rock support is the sum of the swelling and the gravitational pressures and possible mechanical squeezing forces (Fig 4). Under equal external conditions the clays with the highest swelling properties will cause the highest swelling pressure. The consolidation of a zone is, however, an important external factor, which on the one hand can mobilise high swelling pressures, and on the other increase the gravitational pressure.

The principles of calculating the maximum swelling forces from the zone are as shown below.

The relationship between these parameters is given by the equation

$$P_g = P_l \times \frac{c}{100} \times \frac{K}{k_l} \times B_l$$

where

P_l = the maximum swelling pressure (corrected for elastic expansion) measured in the laboratory with a consolidation pressure of 4MPa (Fig 2);
c = content in per cent of material less than 20 microns (μm) in the sample taken from the zone;
K = actual consolidation (in MPa) of the material in the zone;
k_l = consolidation applied in the laboratory (4MPa);
B_l = the clay thickness, i.e. the sum of all clay fillings in a section across the zone (Fig 5). If the total width of the zone containing clay is much larger than the span or the height in the tunnel, the latter is used in the calculations.

The maximum consolidation (K) of a zone in relatively flat areas can be estimated roughly from the location of the zone in the rock masses, i.e. from the rock stresses caused by the overburden. The knowledge of possible high tectonic stresses occurring in the rock mass and the direction of these are not important in this rough assessment. This is because such zones are easily compressed and deformed by shear forces.

If pore water pressures and rock stresses have been measured, the in-situ effective stresses across the zone have to be more precisely considered. The maximum stresses acting across clay zones in steep valley sides may in some cases be particularly high. This is the case where the zone strikes parallel to and slopes inwards from the valley.

For flat topographical conditions, the correlation can roughly be expressed as:

$K = h \times (r_R - r_w)$

r_R and r_w = density of rock mass and water respectively
h = the overburden (in m)

Fig 5 gives an example of how the thickness of the clay fillings, B_l, are defined. If large differences in swelling properties exist between two present clays, B_l should be measured for each of the two types, and the swelling load be calculated as the sum of the two.

At many larger swelling zones, gravitational loads will act on the rock support. This is particularly true if some swelling of the gouge material is allowed; it is caused by a reduction of the internal friction when that material increases in volume and softens (Fig 4).

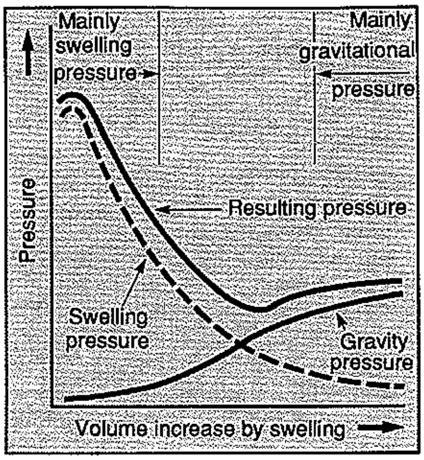

Fig 4. Stages of the pressures resulting from a large swelling zone on the rock support.

With time, may gravitational loads also occur in zones where water leakages have dissolved calcite veins, regardless if the zone containes swelling material or not.

Gravitational load

The gravitational load from a swelling clay zone is a function of many parameters. The main ones are:

- □ size and orientation of the zone in the tunnel;
- □ structure and content of soft materials with low shear strength (clay, chlorite and in particular talc);
- □ consolidation of the soft material;
- □ high tangential stresses across the zone caused by the tunnel;
- □ rock support method and time elapse between tunnel excavation and support installation;
- □ access of water after excavation and during operation of the tunnel;
- □ content of soluble minerals;
- □ joints in the adjacent rock masses, and their orientation with respect to the tunnel periphery. (If not supported by rock bolts, this could be the dominating load.)

The gravitational load will mostly be low if swelling results in no increases or a small volume of them. An example is the support with shotcrete shown in Fig 4. As high gravitational loads are mostly associated with concrete linings, it is recommended the gap between the roof and the concrete be partly grouted. The purpose of this grouting is to reduce these loads when found necessary. Water leakages must not be prevented however.

It might be of interest to know if the support chosen will collapse or not when deformation by overloading is observed. If wet conditions and no washing out or dissolving occurs at moderate depth in hard rock, the pressure in the zone will be maintained and the swelling will stop, which means that a future collapse will probably not take place.

Swelling forces from the zone	=	Max. swelling pressure measured in the lab	x	Correction for content of particles <20μm in the collected sample	x	Correction for consolidation pressure of the zone	x	Thickness of the clay fillings in the zone

Principles of calculating maximum swelling forces from the zone.

With regard to the load bearing capacity of support, refer to the studies made by Holmgren and Hahn, and by G Fernandez-Delgado et al[3,5,11].

Lining through swelling zones

Zones containing swelling clays will behave quite differently in dry and in wet tunnel conditions. Under dry conditions, no swelling will occur, which will cause stability problems. The main task here is to detect that swelling materials are present and to carry out investigations for the purpose of obtaining enough information to be able to dimension the final rock support for the future conditions the tunnel will be subjected to.

If the swelling materials obtain access to water during or after excavation, then swelling can be observed shortly afterwards. In rock masses with short stand-up time, where collapse may involve larger volumes, the speedy installation of rock support is important. The use of shotcrete seems at first most attractive as initial support. This method, however, requires a thorough description of the rock mass conditions and sampling of the clay and of the possible altered rock material *before* the shotcrete is applied and the rock masses covered, making later observations impossible. The information obtained will later be used for assessment of the final rock support.

While shotcrete has been destroyed several times by swelling forces in Norway, no collapses have occurred when unreinforced concrete horseshoe linings have been used as initial support provided the minimum thickness was 5% of the tunnel span (minimum 30cm). The whole profile in a section has to be lined continuously with good-quality concrete with larger thicknesses in high, planar walls. The reason for this positive experience is the arching effect of the lining and the fact that this method allows some initial swelling to take place, which highly reduces the mobilised swelling pressure on the construction.

Shotcrete is best used to increase the stand-up time in rock masses of very low stability, thus preventing collapses and rock falls during concrete placing.

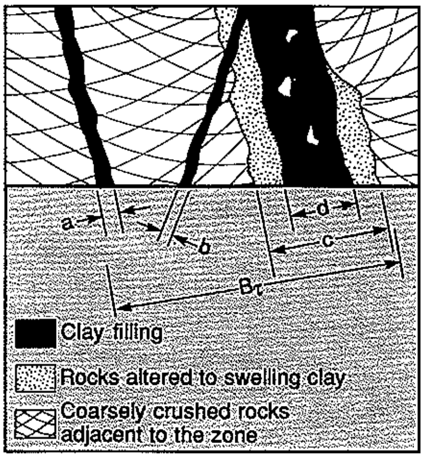

Fig 5. Field measurement of the thickness of clay fillings. With swelling clay only in the fillings, $B_I = a+b+d$. If two types of swelling clay occur, B_I will be $a+b+d$ and c-d respectively. B is the total thickness of the zone.

It is important in all tunnel constructions to prevent progressive collapse taking place and developing. In swelling zones with especially short stand-up time a pore pressure reduction and small step-by-step excavation and rock support by shotcrete followed by concrete lining, as mentioned above, has been found most useful in preventing collapses from starting.

The removal of collapses caused by swelling clays is often a hazardous job. When progressive, larger collapses occur in swelling zones, individual rock falls of various sizes will take place at unpredictable intervals. In cases where the collapse opening is covered by the collapse material, it is often impossible to know how the collapse has developed. Attempts to stablise such loose material by grouting and bolting have not been successful. Stabilising by freezing requires water-saturated, tightly packed material and low groundwater movement. The forepoling method requires a very low content of larger blocks, and a reasonable friction angle of the collapse material. Before the tunnelling method is chosen, it is important that the situation be carefully examined and considered in its entirety.

The best solution for tunnelling may be achieved with a by-pass tunnel which is excavated by a step-by-step excavation and rock support (Fig 6). This is best done in water tunnels where variation of the alignment is of no consequence. If the material in the zone has a very low consolidation, long drainage holes have to be drilled high above the roof in order to reduce the pore pressure before the by-pass tunnel advances into the zone.

Tunnel collapses caused by swelling clay zones have taken place in Norway for the following reasons:

- □ high swelling pressure acting on shotcrete supports;
- □ large gravity loads by the rock material caused by loss of friction and shear strength as a result of swelling;
- □ high water pressure build up.

As in most other fields of engineering the best understanding of the processes taking place is often gained from failures. The experience collected from tunnel failures in swelling zones has given valuable information used in the development of laboratory procedures as well as in the principles for calculating the pressure on the rock support.

The failures have also shown the consequences of underestimating the swelling rocks. Swelling zones must therefore be treated seriously both with regard to sampling and description of the rock mass as well as assessment of the loads to be applied in the design of the rock support. This is particularly important when shotcrete is used.

In spite of several collapses in swelling zones in water tunnels in hydroelectric power plants in Norway, most of the repair work was carried out without expensive loss of electricity production. This is due to the fact that the work was done at a time when the water could be collected in the reservoir(s). The cost of the repairs has, however, in some cases been considerable.

Acknowledgement

As in most other cases where geology is involved, a great variety exists in the

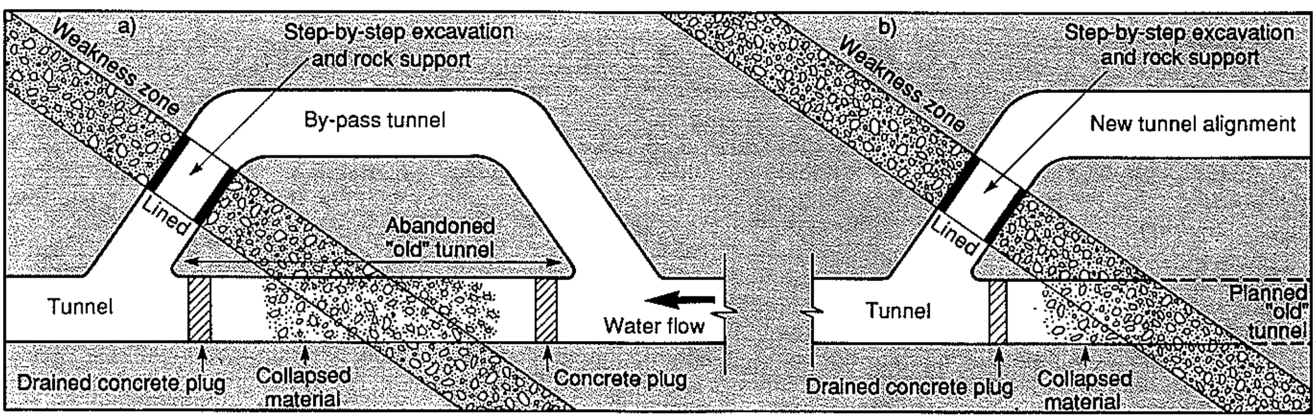

Fig 6. Examples of by-pass solutions if large, progressive collapses occur in tunnels conveying water: a) slide occurred after tunnel excavation was completed; and b) during tunnel excavation.

occurrence and behaviour of swelling clay zones. The difficulties in systemising all the factors involved to make this interesting subject accessible to readers is fully emphasised. Dr Syver Froise, Berdal Strømme AS, has kindly made valuable improvements in the text and has corrected the English. □

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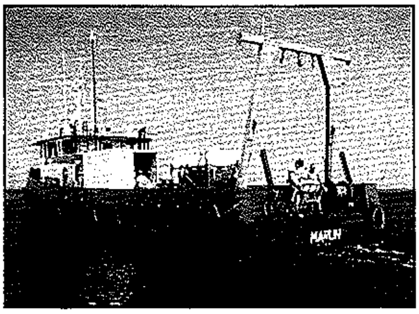
Going for gold

The British Department of Trade & Industry (DTI) Enterprise Initiative and the Quality Scheme for Ready Mixed Concrete (QSRMC) have joined forces to make a video, 'Going for Gold,' whose message is clear: quality is the key to competitiveness and will pay dividends after 1992. QSRMC itself received quality approval in January 1989 when it received a certificate of accreditation from the National Accreditation Council for Certification Bodies, a national body set up by the DTI in 1985 to uphold the standards of certification bodies. The standards set by QSRMC require certified companies to operate a quality management system in accordance with BS 5750 1987. **Express Enquiry 108**

Offshore oilfield technology aids Boston Harbour survey for clean-up

Marine geophysical surveying techniques adapted from offshore oilfield technology are being employed by Mott MacDonald on the $6bn Boston Harbour Clean-up project. As the harbour geology is complex and difficult to survey conventionally, geophysical pro-



filing with muti-channel digital surveying is being undertaken to expand geological data required for the 8km cross-harbour wastewater tunnel and 15km ocean outfall involved in the clean-up project (*T&T,* Oct '89, p35).

In a $450 000 contract including computer processing and geological reporting, the offshore surveying work around Nut Island and Deer Island has produced some 240km of digital data, which is currently being processed in Houston by Texseis. Favourable weather conditions enabled the contractor, Seattle-based Williamson and Company, to complete the survey in just eleven days. The contract was awarded by Mott Hay Inc, part of the Mott MacDonald Group. Mott Hay Inc is acting as subconsultant to Metcalf & Eddy, the lead design engineer, on the Boston Harbour Clean-up project for the Massachusetts Water Resources Authority.

Mott MacDonald and specialist engineering geophysical consultant J Arthur & Associates applied similar techniques on the Channel Tunnel to predict key strata levels. The two firms are currently working in association to develop further oilfield technologies for civil engineering, in particular the use of land-based vibroseis surveying.
Express Enquiry 105

Japanese jumbos

European hydraulic drilling jumbos are well known and widely used, but Japanese models have so far tended to be used only in Japan or by Japanese contractors working abroad. As with other Japanese equipment, it is only a matter of time before the scene will change.

Furukawa manufactures a successful all-hydraulic 3-boom wheel jumbo capable of drilling large tunnel sections up to about 11m high and with cross-sections of 25m^2 to 100m^2. The operator deck is movable up and down in accordance with lifting and lowering of the boom yoke.

The variable stroke drifters make drilling possible in all rock types from soft to very hard. The multifunction boom diminishes overbreak. The same jumbo can be used as a 2-boom machine since one boom may be demounted.

The Furukawa offers rapid boom positioning, fast travelling capability, a charging cage capable of covering a wide area, and safe drilling because of its special anti-jamming mechanism. The low noise level, good, mist-free visibility, reduced vibration and exhaust gas cleaning system give improved working conditions in the tunnel.

The electric cable and water hose reels are hydraulically driven. As you might expect on a Japanese machine, there is a wealth of automatic controls and safety devices. The automatic guide shell parallelism device is operable both horizontally and vertically. The booms are rotatable through 400° and extendable over 1.6m. The jumbo has a distinguished slope-climbing performance with 4-wheel drive.

Jumbos are equipped with the hydraulic drifter HD135, which has a built-in adjuster controlling the impact rate and impact force to suit the rock type of the tunnel face. Elongated pistons improve impact energy transmission efficiency which, it is claimed, gives better drilling performance even on very hard rocks and extends bit and rod life.

All kinds of advantages are usually claimed by equipment manufacturers, but the real test comes when the contractor actually uses the machine to drive a tunnel. Japanese equipment has been underestimated in the past, but has often turned out to be the world's best in the long run. Only time will tell when and whether Japan's drifters and jumbos will beat the best available in Europe. But we are sure to see more of them about outside Japan. **Express Enquiry 106**

Construction health

The Building Advisory Service (BAS) has combined with Environmental Management to provide more information on achieving a healthier environment for the construction industry. The newly formed team has the expertise to deal with: noise surveys; building surveys to locate hidden hazards; toxic substances reviews; monitoring dust, gas and chemicals; safety policy reviews; in-house and public training courses; site health checks and first-aid training.

New legislation places responsibility on employers to take more care over employees' health. **Express Enquiry 107**