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# Tunnelling in Squeezing Rock- Yielding Elements and Face Control

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Major deformations may occur in a tunnel driven through squeezing rock which eventually may necessitate the re-construction of the cross section. The resistance of the tunnel support (shotcrete lining, steel arches, rock anchors, etc.) to the convergence induces large rock pressure which may exceed the support's load bearing capacity. The rock pressure may cause a stability problem. An economic way to reduce the rock pressure is to allow controlled deformations. For this purpose a tunnel's steel arches may have sliding connections (TH - profiles) and the shotcrete lining may include yielding concrete elements in longitudinal slots.

This paper reports experience on construction using the recently developed **HDC Elements (High Deformable Concrete)*** in several tunnels. The HDC Elements have a beam shape and are longitudinally fixed to the excavation surface at different locations. The elements are incorporated into the tunnel lining when the shotcrete is added. If the lining becomes subjected to a radial rock pressure of the designed value the normal force in the lining will cause the HDC Elements to yield thus preventing the shotcrete from being overstressed. HDC Elements yield at a pre-selected stress level (8 to 12 MPa) and maintain the load during their compression of up to 50%. Use of HDC Elements in the strongly squeezing section of the deep 34 km long Lötschberg Base Tunnel in Switzerland has demonstrated the engineering and economical advantages of this construction method.

Full face excavation in squeezing rock is nowadays the most frequently used construction method. Its prerequisite is, however, a stable tunnel face which is achieved by systematically placing long anchors ahead of the excavation. Continuous monitoring of displacements along the tunnel axis ahead of the face is a reliable method of checking the efficiency of the stabilizing measures and safety of the construction. This procedure allows control of every individual step in the advancement of the face as well as observations of deformations with time.

The RH-Extensometer (Reverse Head) was developed to make continuous measurements ahead of the tunnel face. Measurements are made even with the successive destruction of the measuring rods that occurs during the excavation procedure. This is possible because the head of the extensometer,

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* **Note:**
The term "HDC-Elements within this paper is out of date.
The new registered name is "hiDCon-Elements.

containing the sensors and a data logger, is placed at the base of the borehole (i.e. it is the furthest away from the tunnel face and the last to be reached). The recorded measurement data are transferred to the face of the tunnel by radio transmission. RH-Extensometer monitoring has a great advantage over commonly used Sliding Micrometer measurements because the monitoring has no effect on the excavation procedure. Practical experience from using the RH-Extensometer during the construction in highly squeezing rock, part of the 57 km long Gotthard Base Tunnel in Switzerland, is reported. Convergence of up to 0.5 to 0.7 m regularly occurs in a controlled manner during excavation of the 13m diameter twin tunnel.

Keywords: HDC Elements, swelling rock, squeezing rock, RH-Extensometer

## INTRODUCTION:

Today an increasing number of long tunnels are being constructed that have sections in significant overburden. As a result, safe and economic ways to tunnel through squeezing and swelling rock has become important. This paper presents geotechnical solutions to these difficult engineering conditions by using new types of tunnel support, the recently developed yielding HDC Elements. Additionally, a new device to continuously monitor the axial displacement ahead of the tunnel face is described.

## TUNNELLING IN SQUEEZING ROCK

The planning of long, deep base tunnels through the Alps in France, Italy, Austria and Switzerland has put more focus on the problem of tunneling in squeezing rock. Frequently in underground constructions it is observed, that an excavation leads to major long-term rock deformation. If the deformations develop completely, the rock penetrates inwards (into the opening) from all sides, including the tunnel floor. On a closer examination of such phenomena it appears that the resistance of the lining induces compressive stresses at the rock/ lining interface. These stresses are called rock pressure. With regard to the rock, one speaks of lining resistance, with regard to the lining of a load.

Investigations of the Swiss Federal Institute of Technology Zürich [1] show up the correlation between rock pressure, lining resistance and deformation.

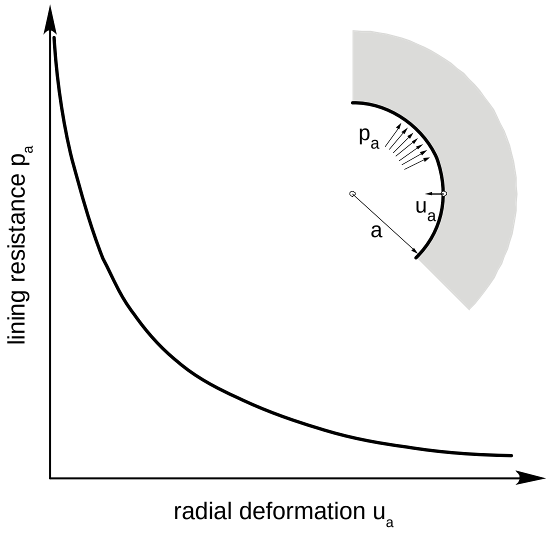


Figure 1: Lining resistance vs. deformation

Figure 1 shows the characteristic curve of the relationship between lining resistance and radial deformation. For a detailed description of the characteristic curve the reader is referenced to literature [1], [2] and [3].

As shown in Figure 1, a high lining resistance leads to low convergences and a low lining resistance instead leads to high convergence. In the extreme case a rigid lining would result in no convergence and no lining would result in the tunnel collapse. From this it follows that a rigid shell or liner would be the best solution. However, because of technical and financial reasons a rigid shell is rarely considered.


Figure 2: 1:1 In-situ Test of steel arches, Sedrun, Swizerland

The construction at one Gotthard base tunnel sites, Sedrun, is described as an example for tunneling in squeezing rock. The overburden in some highly squeezing rock zones is as much as 2400m. Therefore a lining resistance between 7 and 11 MPa would be recommended. If you allow a certain amount of controlled deformation the required lining resistance can be lowered to 2 – 3 MPa. The best way to apply these controlled deformations is a deformable lining with a constant deformation resistance. At the end of the deformation range the resistance should increase and meet in the desired lining resistance to stop the convergence. The sooner the deformation- and lining- resistance are equal, the smaller the zone of rock loosening around the excavation. In an attempt to control deformations TH profiles with sliding connection are used at the Gotthard base tunnel. After the full face excavation a thin shotcrete sealing is applied to the rock and steel arches are installed. When the permitted convergence has occurred a 300mm thick shotcrete layer is spread. This happens about 60m behind the tunnel face. A circular steel arch, consists out of 8 TH-44 profile segments and 16 sliding connections which allow a radial convergence of 700mm and a lining resistance of 1MPa, is installed. Several 1:1 in-situ experiments (Figure 2) have been conducted to verify the parameters of the TH profiles. These profiles have been used in mining for some time but this is the first time they have been used in tunneling with a diameter of 13m. To date, several kilometers under difficult engineering conditions have been successfully constructed.

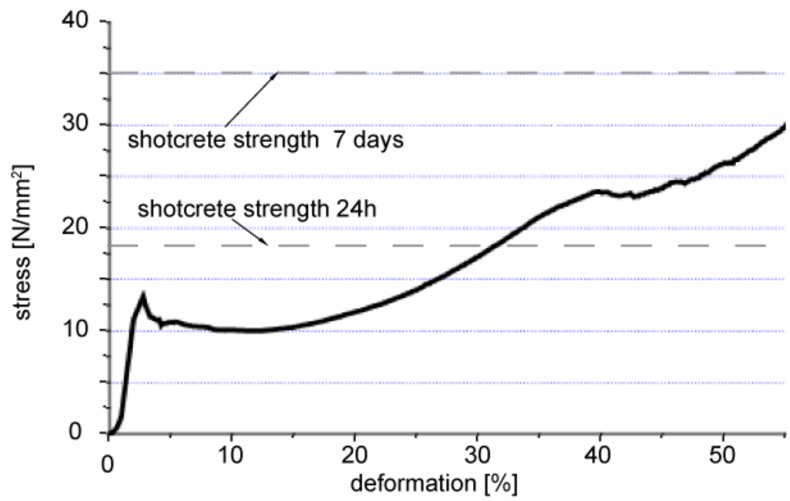


Figure 3: Characteristic Stress – Stain diagram of a HDC element

To optimize this system by increasing the deformation and lining resistance the HDC (High Deformable Concrete) elements have been developed. The compressive strength of the HDC elements can be adjusted between 4 and 18 $N/mm^2$. The deformability of up to 60% depence on the resistance of the element and the limits of the entire structure (see Figure 3).

The HDC elements are installed in slots in the shotcrete lining between the steel arches. By using HDC elements, the shotcrete lining can deform without failure along with the steel arches, adding to the resistance of the complete system. The resistance of the installed system was predefined to be up to 3 MPa. The system resistance depends on the diameter of the tunnel, the thickness of the shotcrete and the parameters of the HDC elements. With HDC elements installed in the shotcrete liner gaps a much higher deformation resistance is achieved from the start.

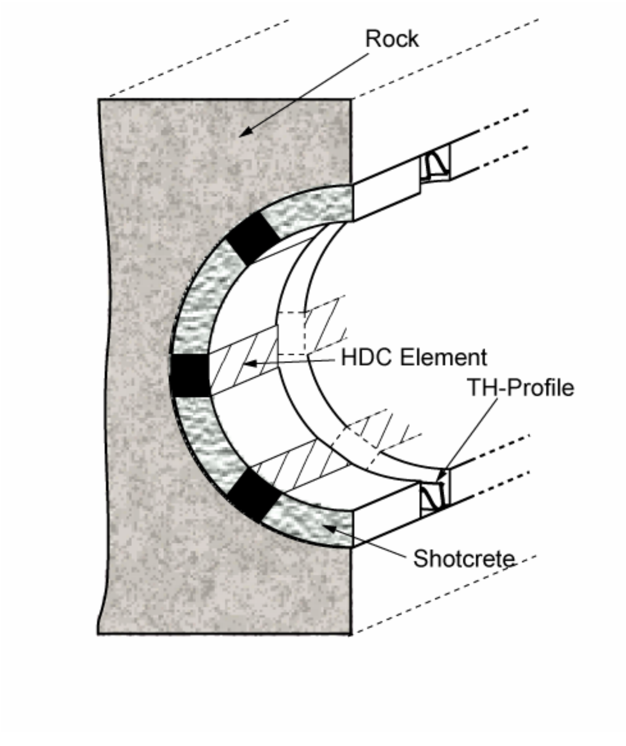


Figure 4  Lining system with HDC Element

An unexpected squeezing rock zone was found very close to the cut-trough of the Lötschberg base tunnel (l=35km). The previously used tunnel lining (consisting of steel arches, anchors and shotcrete in a horseshoe profile) could not withstand the high pressures and deformations in the squeezing rock zone. Instead, a tunnel lining with a circular profile, steel arches, anchors and deformation gaps in the shotcrete was used. The gaps in the shotcrete were empty so the deformation resistance was applied by the TH-profile and the anchors. The shotcrete shell only starts to establish lining resistance when the gaps are closed.

It turned out that big parts of the shotcrete are destroy by the deformations so it could never build up a lining resistance. These sections of the tunnel have been re-profiled and renewed with the aid of HDC elements. (See Figure 4 - 6). After very good experienced with the system and HDC elements (less convergences, earlier stabilization of the deformations and economic savings) the HDC elements were installed directly behind the tunnel face for the remainder of the tunnel advance in the squeezing rock.

HDC elements are also being used at St. Martin la Porte, one of the site access tunnels of LTF base tunnel where the geology makes tunneling difficult because of highly squeezing rock.

Figure 5: Deformable lining with HDC elements in Lötschberg base tunnel

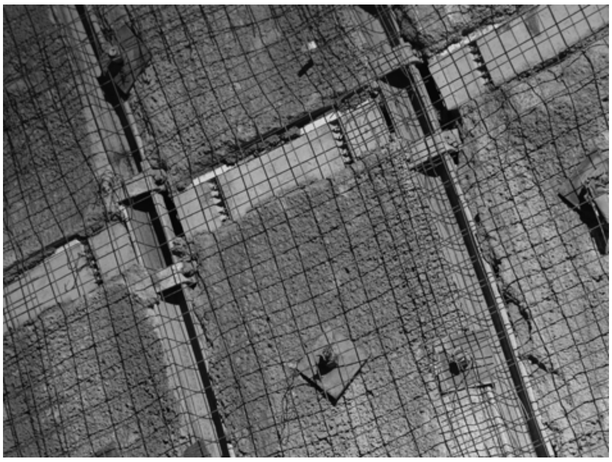

Figure 6: Detail of an installed HDC elements

## APPLICATION OF HDC – ELEMENTS IN SWELLING ROCK

Rocks containing clay minerals or anhydrite increase in volume when they come in contact with water. This phenomenon is referred to as the swelling of these rocks. Tunneling in swelling rock normally causes two different types of damage. The first type results in the failure of the invert arch due to the pressure from the swelling surrounding rock. The second type occurs under low overburden conditions where the tunnel lining remains intact and results in heave of the entire tunnel. The tunnel crown and floor experiences an upward displacement. [4]

The Chienberg road tunnel, Switzerland, was designed with a circular profile based on the resistance principle. As the main tunnel section was nearing completion swelling rock caused the entire tunnel to heave. Heave of up to 10 centimeters occurred in two tunnel sections with low overburden. Damage affected a 60 meter section and another 370 meter section of the nearly 1.5 km long tunnel. [5]

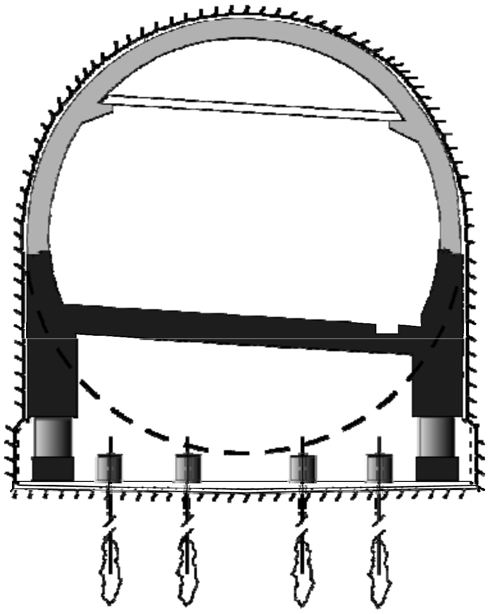

Figure 7: „Modular Yielding Support“

These two tunnel sections were redesigned by Prof. K. Kovári according to the “Modular Yielding Support” concept. In this concept HDC foundation elements are placed under the lining pillars and other HDC anchor elements with tie back anchors are mounted on the tunnel floor. To put this plan into practice the concrete floor of the tunnel lining in the two affected sections had to be removed in stages. A 6m deep trench had to be excavated below the original floor to build the new floor for the modified system. The new carriageway slab is 4 meters above the new floor and has bending resistant connections to the remaining tunnel structure (Figure 7: The dashed line shows the original profile).

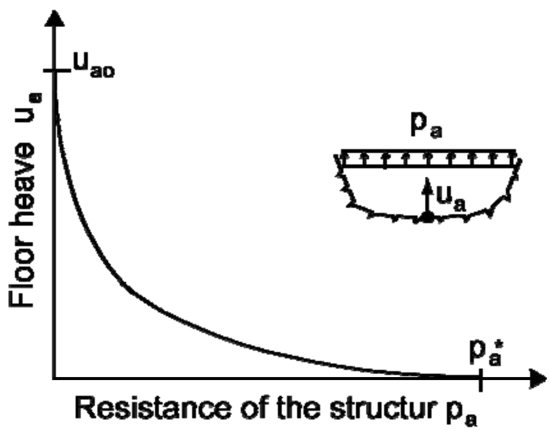


Figure 8: The characteristic line for swelling rock

The concept of the “Modular Yielding Support” is based on an interaction between rock deformation due to the swelling and the resulting pressure caused by the resistance of the structure. Figure 9 shows the qualitative relationship between stress and expansion of swelling rock. It is based on the “swelling rule” for clay rocks, from oedometer tests [6/7].

Figure 8 shows, that permitting extension of the tunnel floor (using deformable HDC elements) results in less vertical stress and a decrease in load of the overlying rock.

The HDC foundation elements have a height of 1000mm and diameter of 900mm and were designed in 3 different load classes for the corresponding overburden. Every type has a defined minimum and maximum level of load resistance. The minimum level prevents tunnel settlements; the maximum level protects the tunnel against overstressing and heave. Within the specified limits a deformation range of 30-40 % of the original height of the elements can occur (depending on the type). The load capacity for each HDC type was customized by varying the mixture and reinforcement within the elements.

To configure the different types of elements to their design parameters several tests had been conducted on the 20 MN load testing equipment at the EMPA (Swiss Federal Laboratories for Materials and Research)

Figure 9 and 10 show characteristic stress-strain-diagrams and the test system.

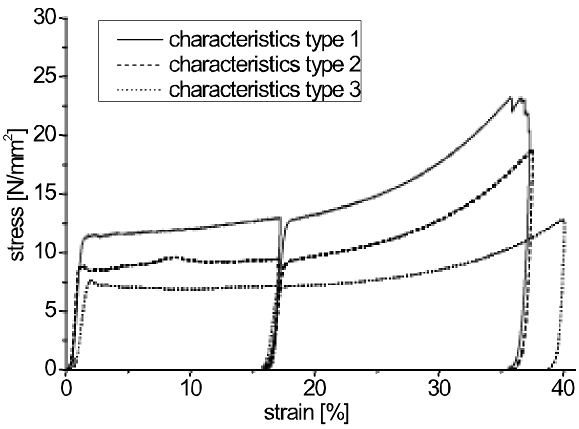


Figure 9: stress – strain – diagram of HDC foundation elements

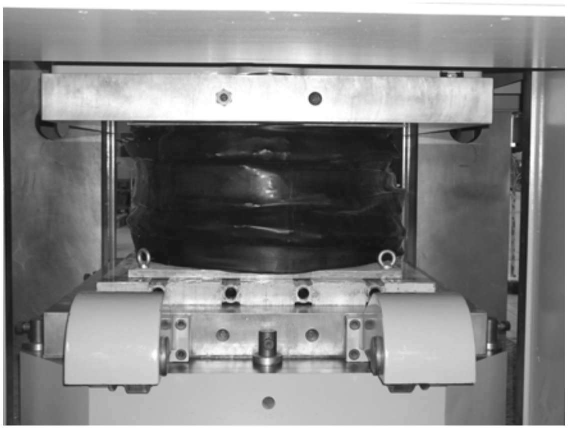

Figure 10: HDC foundation element during load testing

The HDC-Elements at the Chienberg road tunnel are designed for a deforming endurance of about 25 years. The advantage of the "Modular Yielding Support" as it is realized within this project is that it allows the accessibility for observing and exchanging the elements at any time. This allows elements to be individual replaced within the system when their deformation capacity is depleted.

## RH-EXTENSOMETER

The RH Extensometer (Reverse Head) was developed to make continues extrusion measurements ahead of the tunnel face. The Sliding Micrometer or Deformeter is the classic and proven instrument for this type of measurement. These instruments may have several disadvantages. Due to the high pressure and deformations (as in some sections of the Gotthard base tunnel) the measurement casing can be destroyed after a short period of time. Another disadvantage is that the measurements are only taken from time to time and there is no possibility for continues monitoring of the extrusion of the face. The RH Extensometer was developed by Prof. K. Kovári and Solexperts to work in these situations.

The RH Extensometer is a special version of an extensometer with six measuring points. As the tunnel advances the RH Extensometer becomes shorter as the central pipe and the anchors of the measuring points are cut away (Figure 11). The measuring head is at the bottom of the borehole and contains its own power supply, measurement and data acquisition unit. The measurement frequency can be selected between 10min and 24h. With one measurement per hour the power supply is sufficient to log for up to 4 months. The RH extensometer provides three redundant systems of data transfer from the measurement head. The first possibility is via a cable located in the central pipe. The second is by radio link at the tunnel face (the cable acts as an antenna). The third possibility is to insert a long antenna into the central pipe and read out the data by radio. The data can only be downloaded when the central pipe is accessible. Experience has shown that access is usually not a problem. Data is read out fast and causes no significant delay for excavation work.

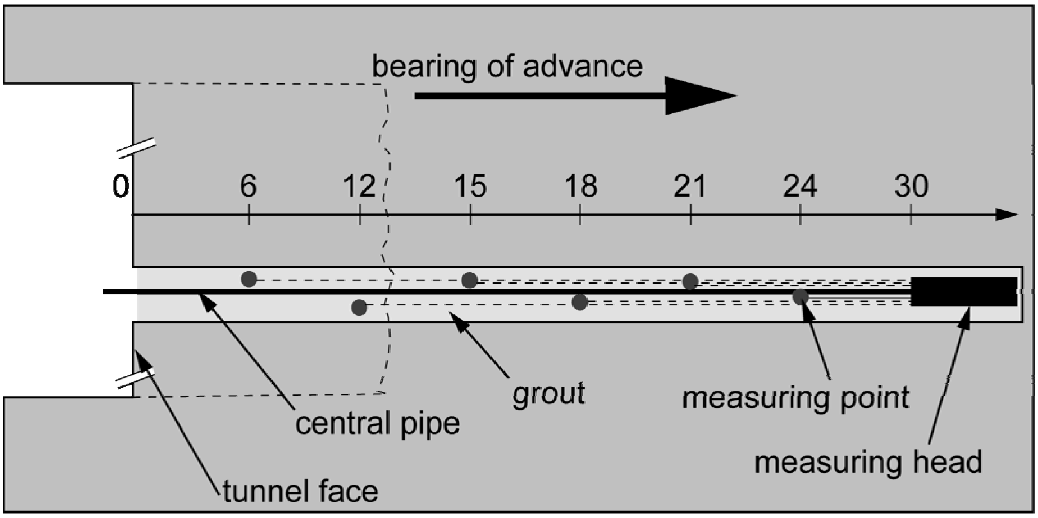


Figure 11: schematic drawing of a RH Extensometer

Several RH-Extensometers have been successfully installed at Sedrun, a section of the Gotthard base tunnel. Even if the central pipe is not accessible after every excavation step, the data is stored and can read out later. Continues monitoring of the face extrusion provides extensions as well as time effects. The data show the direct reaction of the tunnel face to excavation, anchoring and other support options. The anchoring layout as well as the length of the face support, can be optimized to the geologic conditions using these data.

Figure 12 shows a typical report for a RH Extensometer, the displacement of each measurement point and it distance to the face. The time effect is also clearly observable. Deformation speeds up directly after an excavation step and then slows down with the time before the next step. For systematically monitoring of the face extrusion the RH-Extensometer are installed in an overlapping manner.

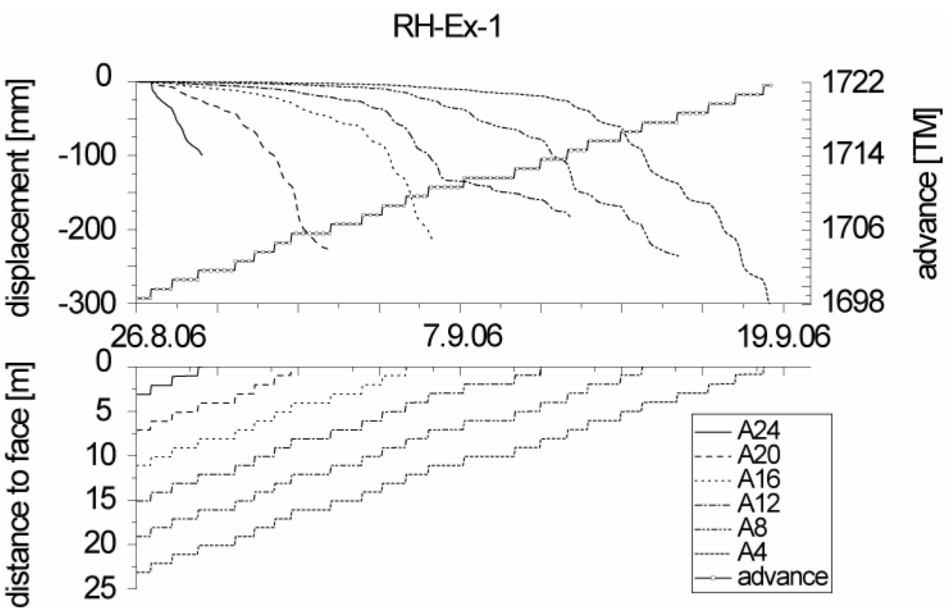


Figure 12 Report of a RH-Extensometer data

The RH Extensometer has a number of advantages over the instruments classically used to measure tunnel face extrusion and is the future for tunnel faces measurements. This continuously recorded data allows control of every individual step in the advancement of the face as well as observations of deformations with time.

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