CALCULATION AND DESIGN OF UNDERGROUND DAMS WITH SPECIAL REFERENCE TO THEIR USE IN ROCK-SALT

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1. PRESENTATION OF THE PROBLEM

In the mining industry dams, which can be separated into static supports for bearing strain and sealing elements for guaranteeing impermeability, are responsible for sealing off workings against fluids and gases. Sealing against water and salt-water is necessary as a preventive measure, after an inrush of water or brine, for securing workings which are in use against those under water, and for draining shafts.Sealing against oils, gases and noxious substances is needed when underground workings are used for storage. In the G.D.R. in the last ten years, national economic requirements concerningsgas storage and potash mining have necessitated the construction of dams under very difficult conditions for which even world-wide no comparable designs exist. This paper will report about the solution of this problem.

2. ANALYSIS OF THE LITERATURE AND PATENTS

An analysis of the loo-year old development of the consruction of cross section-seals permits the following conclusions:

1. Parallel-shaped, truncated cone-shaped and toothed constructions as well as spherical calottes were used predominantly. The geometry was established arbitrarily. The geometry was established arbitrarily. The parallel-shaped constructions are the most widespread /picture 1/.

2. The calculations require, apart from the geometry of the supports, a determination of the shearing stress and bending stress for rigidly fixed plates. These two tindings do not give an approximate reflection of the real stress condition and are therefore unsuitable for the calculation.

3. Excessive loading resulted in several cases in the destruction of static supports.

4. In order to get sufficient impermeability additional measures were necessary /injections/, and absolutely impermeable cross section seals were only obtained in a few cases by using extremely long dams. Attempts to seal off carnallite and sylvinite have not been successful to date.

The analysis of the literature and patents, the existing experiences, and national economic requirements posed the following principale problems:

1. Application of calculation which reflects the real stress condition in the dams.

2. Development of sealing elements with special reference to use in rock-salt.

3. TECHNICAL SOLUTIONS

3.1. Assessing the dimensions of the supports

This resulted in the following problems:

- how to arrive at a suitable model for calculation.
- how to construct good, practicable supports.
- how to evaluate the alteration of the initial parameters.
- how to evaluate the influence of non-linear effects.
- how to choose a suitable criterium of failure.
- how to arrive at the necessary safety factor.

Since an exact calculation of the stress is not possible using analytical methods, the stress condition and displacement were calculated numerically. The programme which was applied, and which was performed with 12o sample calculations, was based on Hook's Law. Findings regarding the rock-bound supports put in place to date /they are inextricably bound to the rock/ showed high degress of tensile stress which reach their maximum on the pressure-side at the point of contact with the rock and which cannot be fundamentally reduced even by lengthening the supports. /Picture 2/. The result is therefore breakages from the rock and fracturing. However, through the insertion between the support and the rock of layers free of shearing stress. The stress can be directed so as to give a more favourable stress condition. The desired triaxial compressure stress condition is reached in mobile simple spherical calottes by full radial loading. The maximum pressure stresses can be approximately calculated thus:

$$\sigma_{III}/p = 0.70\ r/t + 1.30$$

Increasing the thickness of the calotte t above 0.6 r to 0.7r is not advisable since the need for extra excavation and more material rises sharply while the reducution in stress is only small /picture 3/. Partly-loaded calottes and multiple or combined calottes show a fundamentally worse condition of stress due to the appearance of tensile stress /picture 4/. The use of spherical calottes is restricted by bending stresses due to rock pressure, by the difficult technological problems in manufacturing them, and by the possible infavourable curved surface.

An investigation into the stress condition of toothed supports shows, that mobile, multi-tooth supports with teeth between 0.8r and 1.0r in length and angles between 25° on the pressure-side and 15° on the other side are the best. The main draw-back of these supports is that tensile stresses occur over a large area which increase sharply as the elasticityymodulus of the rock decreases. These tensile stresses can be reduced by lengthening the supports but at $l \geqq 4$ r they approach asymptotically a limit-value /picture 5/.

Calculation made on mobile truncated cone-shaped supports show that, allowing for favourable stress conditions and a small amount of extra excavations, supports with angles of inclination between 9° and 15° are favourable. Nearly the whole of the support has a triaxial compressure condition of stress; only in a small area on the circumference does some small degree of tensile stress show up. Using supports with a length $\geqq 2$ r multiple truncated cone shaped supports should be used since thereby the area of the cross section on the pressure side and hence the maximum compressive-stress can be reduced. Supports with a length $\geqq 4$ r bring no improvement in the stress condition. The stresses increase as the rock elasticity modulus decreases. The ratio between maximum value of the compressive-stress and elasticity modulus of the rock can be approximated using a logarhythmic function /picture 6/.

In making the calculations for the support not only the stress of the support but also the stress of the rock as a result of excavations for the support and loading of the support should be taken into account. In this respect the use of truncated cone-shaped supports is best since it entails the lowest additional stresses.

Whereas in many branches of technology safety factors are laid down beforehand, in underground mining it is often left to the design engineer to establish the safety factor. Attemps to determine the necessary safety factor using the theory of probability fail, because the fluctuations of the parameters of calculation are not known. Therefore it was agreed to calculate the safety factor from partial safety coefficients which were weighted according to their influence on the position of failure. Out of 19 influencing factors 12 were not taken into account, either because the statements are very exact, the most unfevourable variants occurred or the influence on the position of stress is negligible. For truncated cone-shaped supports, for example, we arrived at a necessary safety factor of 1.9. These safety factors are limits; inelastic behaviour of the material increases the actual load capacity.

On the basis of the calculations made as to stress and displacement and of the criteria of failure and the safety factors which were worked out a guideline for making the calculations of the supports was drawn up with wich practical problems have already been solved.

3.2. IMPERMEABILITY OF THE DAMS

In addition to mining, static and constructional factors, special importance must be attached to the additional sealing measures, especially in the construction of impermeable dams in rock salt. Since the traditional sealing measures using injections for gas storage and potash mining are insufficient, variants were developed using mechanical elements, sealing packs, and freezing. The use of mechanical elements as the sole sealing measure is not recommended. In addition technological solutions were developed for manufacturing cross section sealsthrough freezing, and even saturated and non-saturared $MgCl_2$ salt-water solutions can be securely frozen. The applicability of this method is limited to special cases or accidents in view of the expense and effort involved. The principle of using packs for sealing entails the insertion in front of the support of materials with the following properties:

- impermeability with regard to the adjacent gaseous or fluid media.
- plasticity to guarantee sealing if the support shifts or the rock moves.
- resistance to ageing and corrosion.

For these purposes, as comprehensive tests have shown, clays and bitumens are suitable. When normal clays and salt clays treated with salt water solution were tested for permeability, the resulting damage to the normal clay from the salt water solution increased the permeability 60 to 100-fold, so that high levels of impermeability cannot be reached using salt clay alone. The main task for salt clay, therefore, should be filling in cracks in the support, rock, and contact area. This cementing ability of the salt clay can be effectively raised by adding sand but then the permeability rises substantially. It is therefore expedient to insert a mixture of salt clay and sand immediately in front of the support, followed by a salt clay pack. A layer of bitumen placed on top of the salt clay serves to seal the overall surface of the cross section and improves the sealing of the contact joints. Bitumens are impervious to, and insoluble in water, chemically stable, are ag-resistant, viscous, and show no effect of being injurous to health. The density and viscosity can be adapted to the requirements using simple measures. Bitumen with a low viscosity clings well to dry, dust-free surfaces though the adhesion is greater than the cohesion. In order to avoid negative effects of the sedimentation of debris when the bitumen, heated to 8o° - 95° C, is introduced, the layers should not be more than 15 cms. thick and a new layer should not be introduced until the previous layer has cooled down to at least 65°C. The loss of bitumen through a hypothetical circular gap between the support and the rock and also into vertical crevices in the rock was calculated and conclusions drawn concerning the necessary quantities of bitumen. Experiments into the effectiveness of joint clay-bitumen packs show that this sealing variant functions perfectly well. After squeezing the fluid out of the clay mixture /6o - 2oo h/ no further leakage of the fluid was found.

In addition to freezing, variants were developed for particularly difficult problems of sealing which exclude the appearance of solubility in the area of the support. Such a technological solution contains the following partial solutions /picture 7/.

1. An inert material, e.g. bitumen and an over-saturated salt-water solution, should be placed in front of the support.

2. The amount of convection and diffusion should be kept small by piling up rocks and building barricades.

3. The unsaturated salt water solution should have the chance to become saturated.

4. Use of an over-pressure area filled with silicon oil which is inert with regard to the rock and the bitumen will prevent penetration of the salt water into the area of the sealing packs.

5. In order to eleminate the possibility of solubility a wall-insulator should be introduced and fixed into radial sealing slits.

6. Using pipes

   a/ pressure is guaged, samples are taken, and secondary injections of salt water are made /pipe 1/

   b/ secondary injections of sealing media are made /pipe 2/

c/ an over-pressure is produced /pipe 3/.

4. EXAMPLES OF THE CONSTRUCTION OF STABLE AND IMPERVIOUS DAMS

The above findings formed the basis of several sealing operations performed on cross sections. Three examples of such operations will be discussed.

4.1. Initial operation for sealing off the cross section in mine-shafts in connection with the construction of a gas storage /picture 8/

Due to the high standards required when sealing off gas, two independent sealing systems were introduced. In the hydraulic system the sealing is done by means of a solution of clay and salt water under over-pressure. The fluid pressure is transferred via sealing packs of NaCl-clay and bitumen to the reinforced spherical calottes of concrete 225, which are separated by oil paper and layers of epoxide-resin from the upper and lower layers of concrete and the rock. The combined seal sonsists of a mechanical and a hydraulic part. The mechanical part is composed of a steel plate for sealing the cross section and a steel suchion under hydraulic pressure which seals the area in contact with the rock. The circular space between the steel cylinder and the rock is under over-pressure from oil, which enables the contact and peripheral zones to be sealed. Calculations using the new method give a permissible loading of the calotte of 5,6 MPa. Owing to the upper concrete layer of the calotte, however, the required radial distribution of forces over the entire upper surface of the calotte is not fully reached. Calculations made with axial distribution of the load of 4o MPa resulted in a safety factor of 1,1 in the area of the calotte under maximum stress. This construction has fully proved itself during more than ten years in which it has been operating, with the pressure in the area of the clay-salt water solution at 4,0 MPa. Injections for keeping the salt water solution under constant pressure decreased continuously.

4.2. Sealing a cross section in the shaft of a potash mine

In the course of reopening part of a mine the salt water level in two shafts had to be lowered and at a depth of ≈ 49o metres a cross section seal at 5,5 MPa introduced. Lowering the salt water level by pumping showed a sharply rising quantity of salt water per metre lowered needing to be pumped out, which was traced to a gas bubble enclosed in the mine. Using a surface rotary drill the gas bubble was punctured and the release of pressure allowed the salt water level to be lowered to the necessary extent. The cross section seal was installed in rock-salt; excavations due to the fresh-water layer caused the diameter of the shaft in the installation area to increase from 625 cms. to 900 cms. Because of rock pressure and simple constructional considerations, treble toothed mobile support 10,5 metres high were installed at a place where the shaft had a diameter of 9 metres. The angles of the tooth-surfaces of 25°, 20° and 15° guaranteed that the trajectories of the main pressure-stress ran vertically to the surfaces of the excavations. The tensile stresses were taken up by a cross-wise reinforcement of the air-side support tooth /picture 9, 10, 11/. A soft P.V.C. foil paced on the smoothed excavation guarantees insulation of the shaft-wall and mobile stratification. Sealing was done by a salt water-clay-bitumen pack.

4.3. Second cross section seal in mineshafts for the construction of a gas storage

As a result of our positive experiences with the first municipal gas storage tank another underground storage tank was planned. To support a load of 9,5 MPa in rock-salt, quadruple truncated cone-shaped supports are installed, with the first one on the pressure-side shortened. The diameter of the shaft is 6,5 metres, the concrete of quality B 300, the concrete elasticity modulus is 2 . 10^4 MPa, the rock elasticity modulus 1 . 10^4 MPa, and the angle of inclination of the supports is 12°, and so the length of the supports required is 11,4 ,etres. The relatively small tensile forces occur parallel to the support excavations and are taken up by reinforcement. Mobile stratification is attained by a sot P.V.C. foil an the free axial displaceability is guaranteed by light plates inserted on the air-side sealing is provided by a 40 cms thick mixture of NaCl-clay-fine sand, a 40 cms thick layer of NaCl-clay and 3,25 cms. of bitumen 200 /picture 12/. With a rock temperature of 27°C and using a 50-year-old storage plant, and taking into account the sedimentation of the debris, the bitumen loss, clay compaction and the dish-shaped formation of the surface of the bitumen, the necessary thicknesses of the sealing packswere arranged so that a minimum thickness of the bitumen of 1 metre was guaranteed.

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Figure 1. Geometric forms of the static supports.

" 2. Lines of similar minimum main stresses σ_I/p in rock-bound spherical calottes and rock-bound parallel-shaped supports.

" 3. Maximum pressure-stresses σ_{III}/p and material volumes V_{KA} of mobile spherical calottes with regard to the thickness of the calotte /excavation radius r = 325 cms./.

" 4. Lines similar minimum main stresses σ_I/p in mobile, partly loaded spherical calottes and in multiple fully loaded spherical calottes.

" 5. Lines of similar minimum main stresses σ_I/p in multiple-toothed mobile supports.

" 6. Maximum pressure-stresses σ_{IIImax}/p in mobile, single truncated cone-shaped supports with different lenths /l/r/ and angles of inclination /α/ in relation to the elasticity modules of the rock /E_G/.

" 7. Sealing variant in easily soluble rock-salt.

" 8. Sealing variant in a mine-shaft with spherical calottes for a gas storage tank.

" 9. Sealing variant in a mine-shaft with triple-toothed dams against pressure of salt water from below.
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2. Rear concrete injection
3. Drainage
4. Injection pipe
5. P.V.C. foil
6. Levelling mortar
7. Rock wall
8. Mixture of salt water-clay-sand
9. Bitumen platform
1o. Steel concrete plate

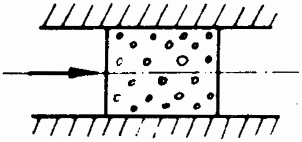
" 1o. Support excavation insulated by PVC foil.

" 11. Air-side reinforcement of the triple tothed support.

" 12. Quadruple truncated cone-shaped support for very high loads.
1. Layer of epoxide resin
2. Saltwater mortar
3. Soft PVC /≈3 mms./
4. Light plate
5. Wall of shaft.

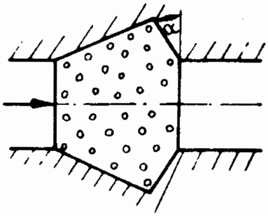
1. Parallele Widerlager

1.1 einfach parallel

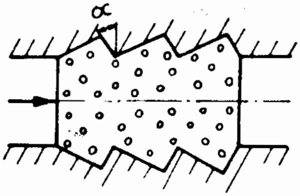


2. Verzahnte Widerlager

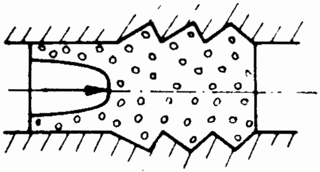
2.1 einfach verzahnt



2.2. mehrfach verzahnt

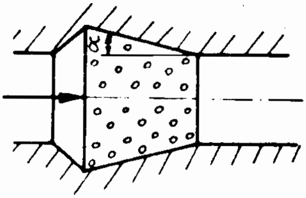


2.3. v-förmig mehrfach verzahnt

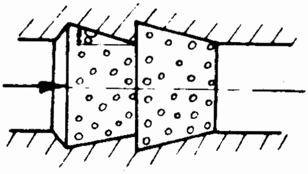


3. Kegelstumpfförmige Widerlager

3.1 einfach kegelstumpfförmig

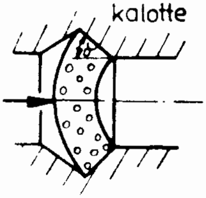


3.2 mehrfach kegelstumpfförmig

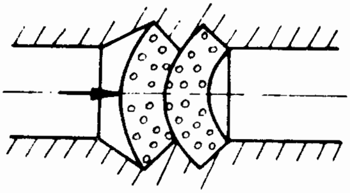


4. Kugelkalotten

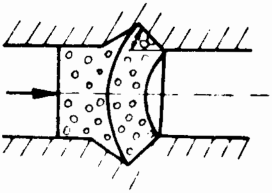
4.1 einfache Kugelkalotte

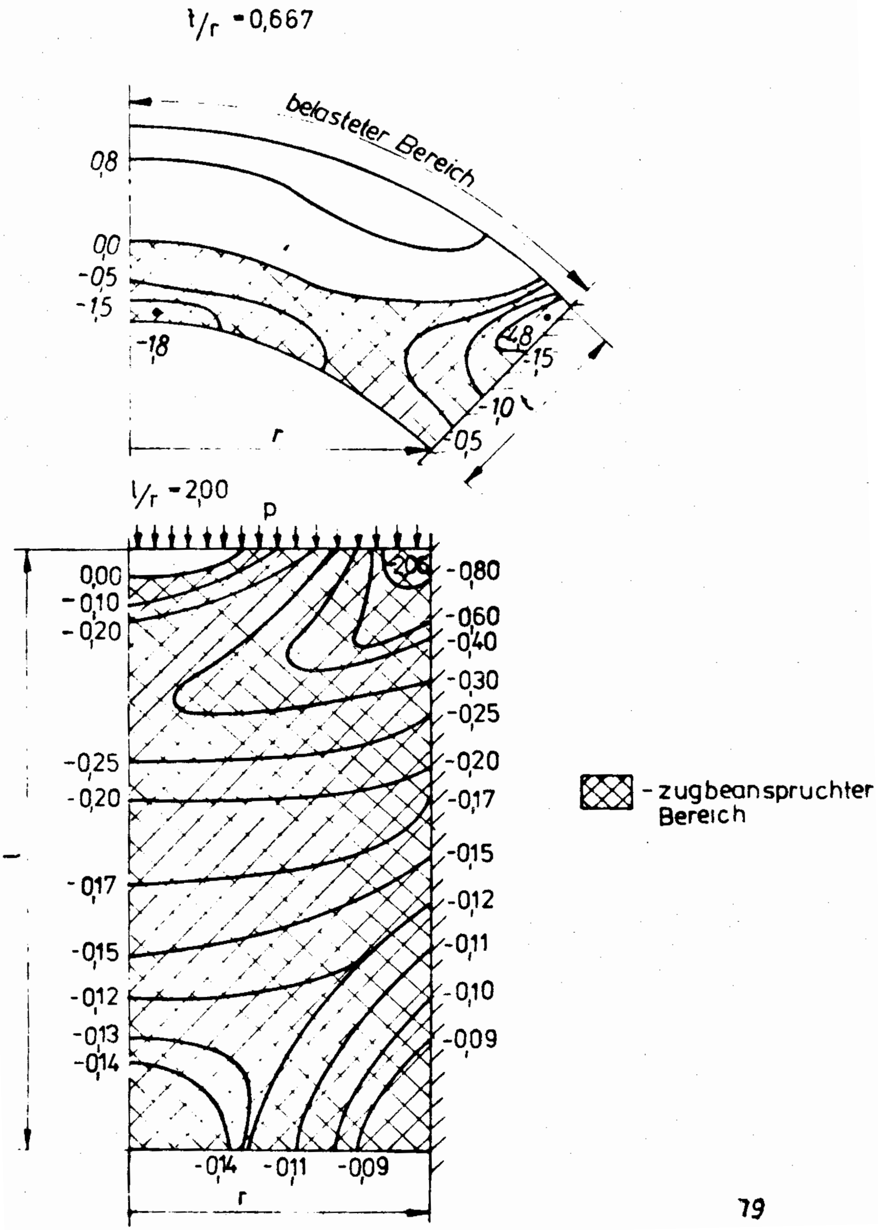


4.2. mehrfache Kugelkalotte



4.3. kombinierte Kugelkalotte




t/r = 0,667
belasteter Bereich
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-0,5
-1,5
-1,8
4,8
-1,5
-1,0
0,5
r
t/r = 2,00
p
-2,06
0,00
-0,10
-0,20
-0,25
-0,20
-0,17
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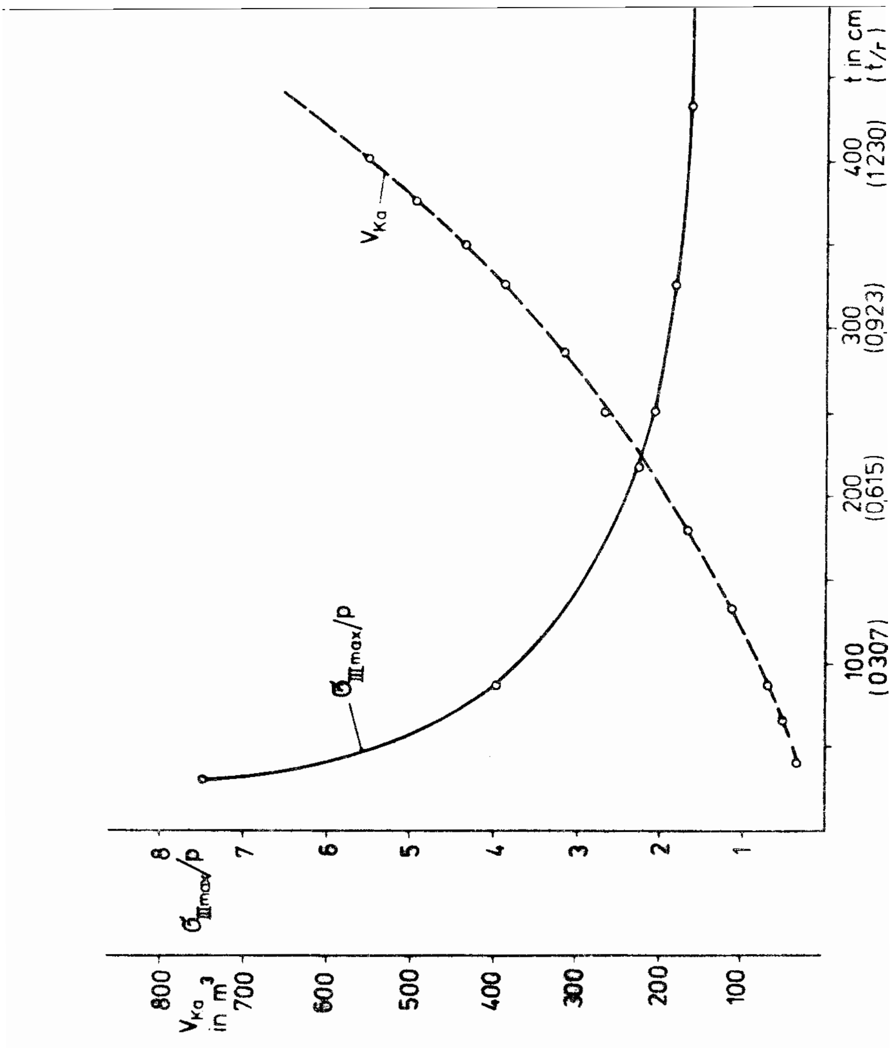
r
▨ - zugbeanspruchter Bereich


V_Ka in m³
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500
400
300
200
100
σ_IIImax/p
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7
6
5
4
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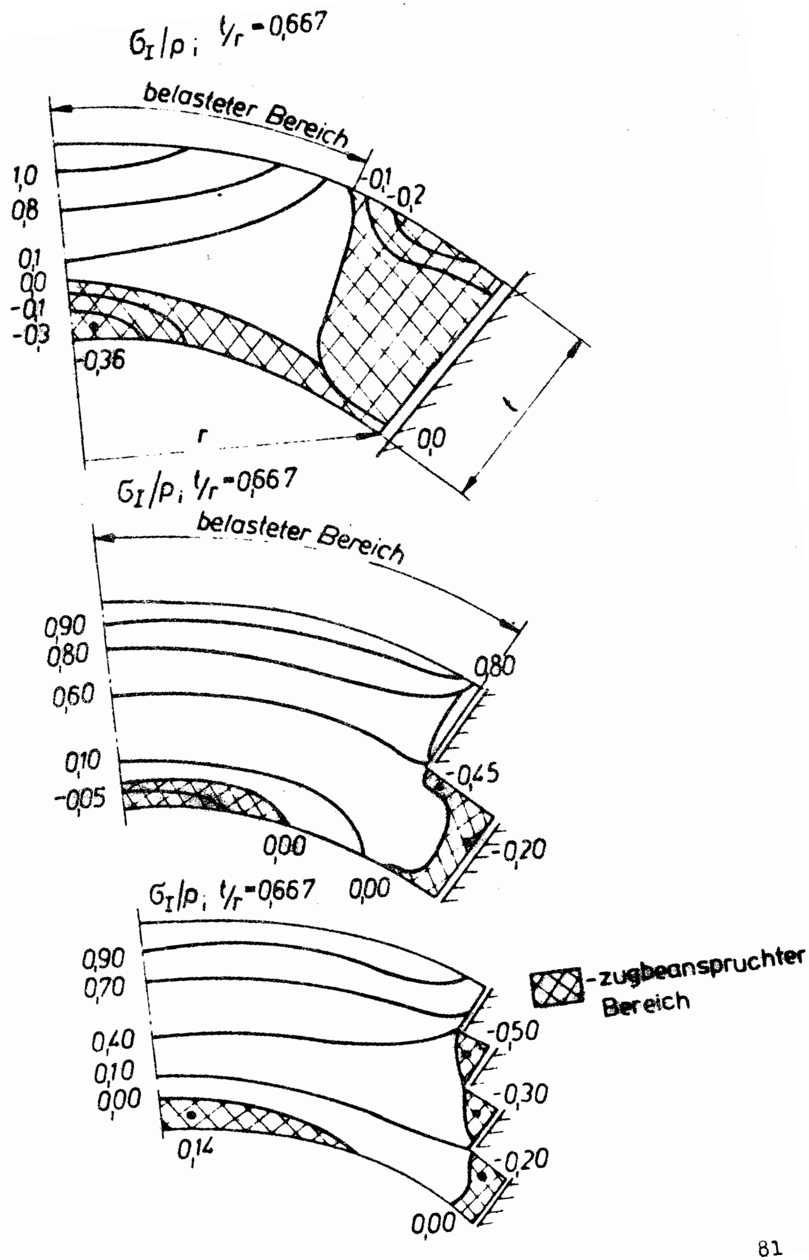
200 (0,615)
300 (0,923)
400 (1230)
t in cm (t/r)
V_Ka
σ_IIImax/p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belasteter Bereich
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0,1
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-0,1
-0,3
-0,36
-0,1
-0,2
0,0
r
t
σI/pi t/r = 0,667
belasteter Bereich
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0,80
0,60
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-0,05
0,80
-0,45
-0,20
0,00
0,00
σI/pi t/r = 0,667
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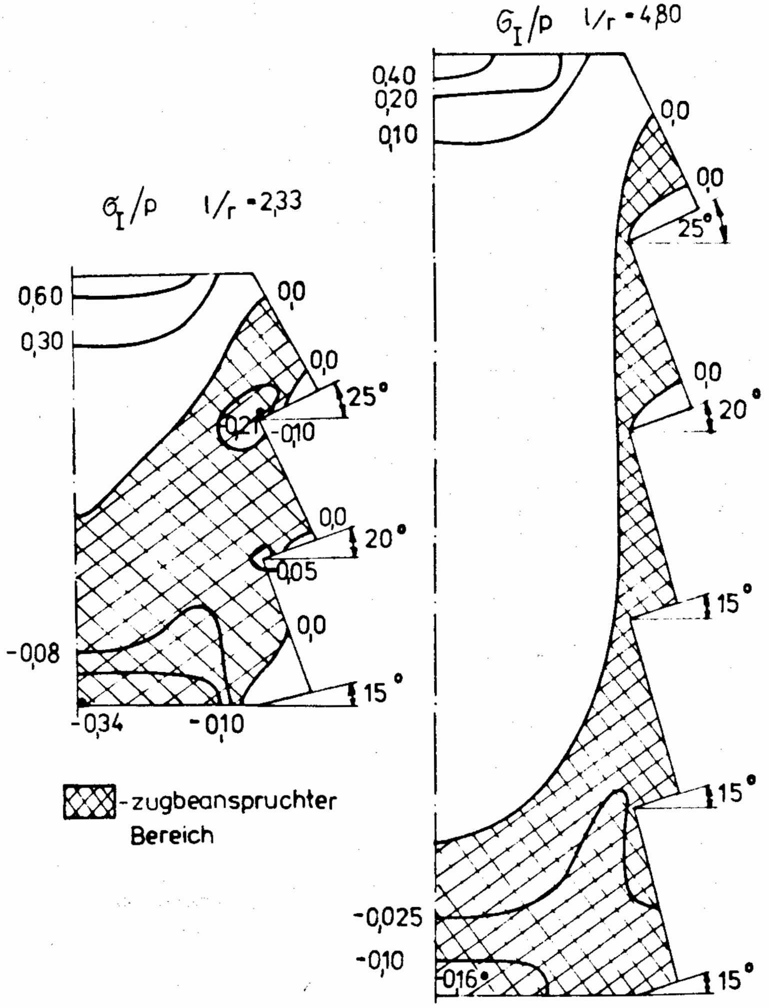
▨ - zugbeanspruchter Bereich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15°
σ_I/p l/r = 2,33
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25°
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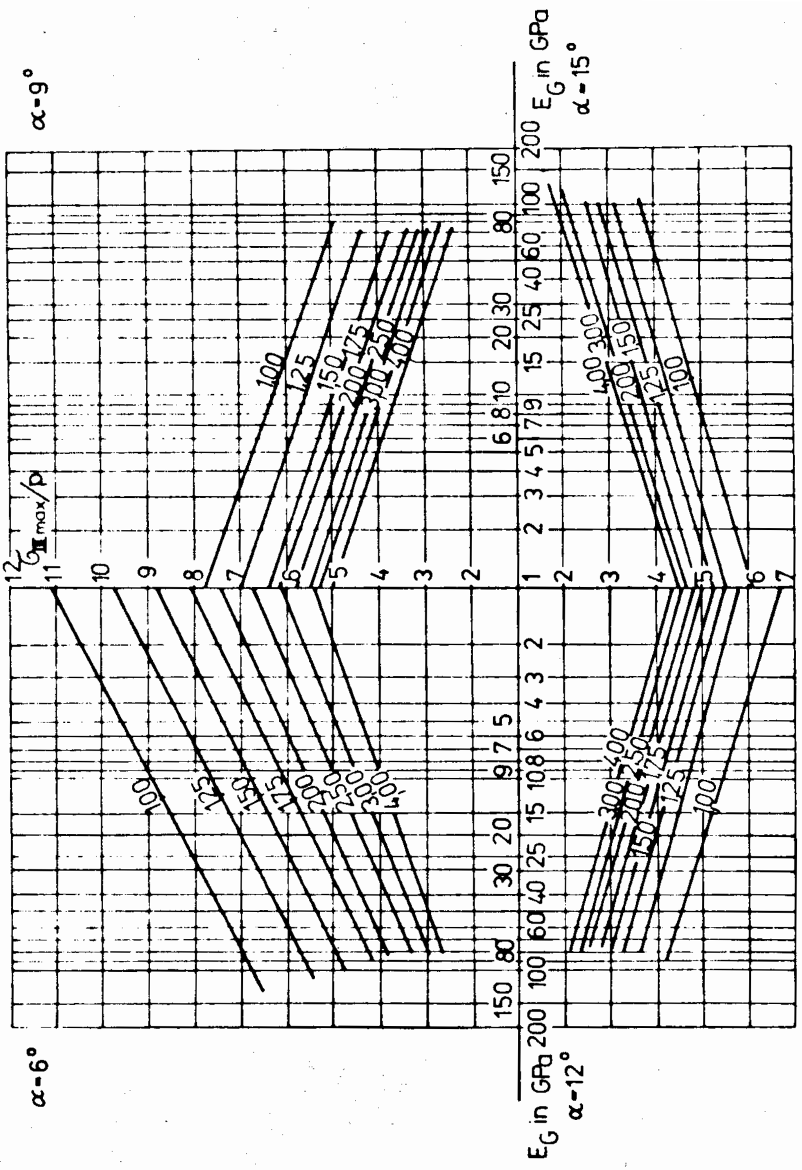
▨ - zugbeanspruchter Bereich


α-9°
α-6°
α-15°
α-12°
E_G in GPa
E_G in GPa
σ_II max/p
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2
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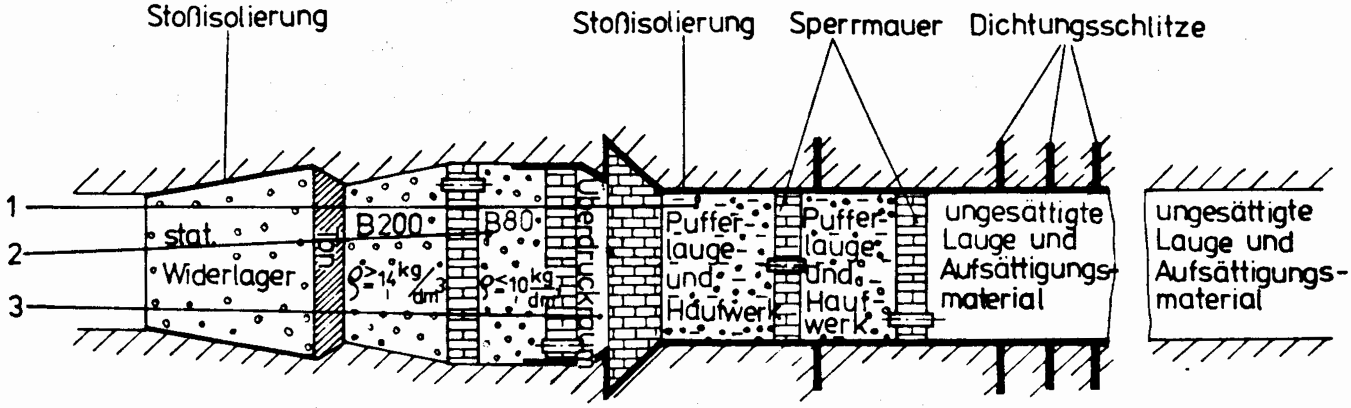
Stoßisolierung
Stoßisolierung
Sperrmauer
Dichtungsschlitze
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2
3
stat. Widerlager
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B80
$\rho \leq 1{,}0 \frac{kg}{dm^3}$
Überdruckraum
Pufferlauge und Haufwerk
Pufferlauge und Haufwerk
ungesättigte Lauge und Aufsättigungsmaterial
ungesättigte Lauge und Aufsättigungsmaterial

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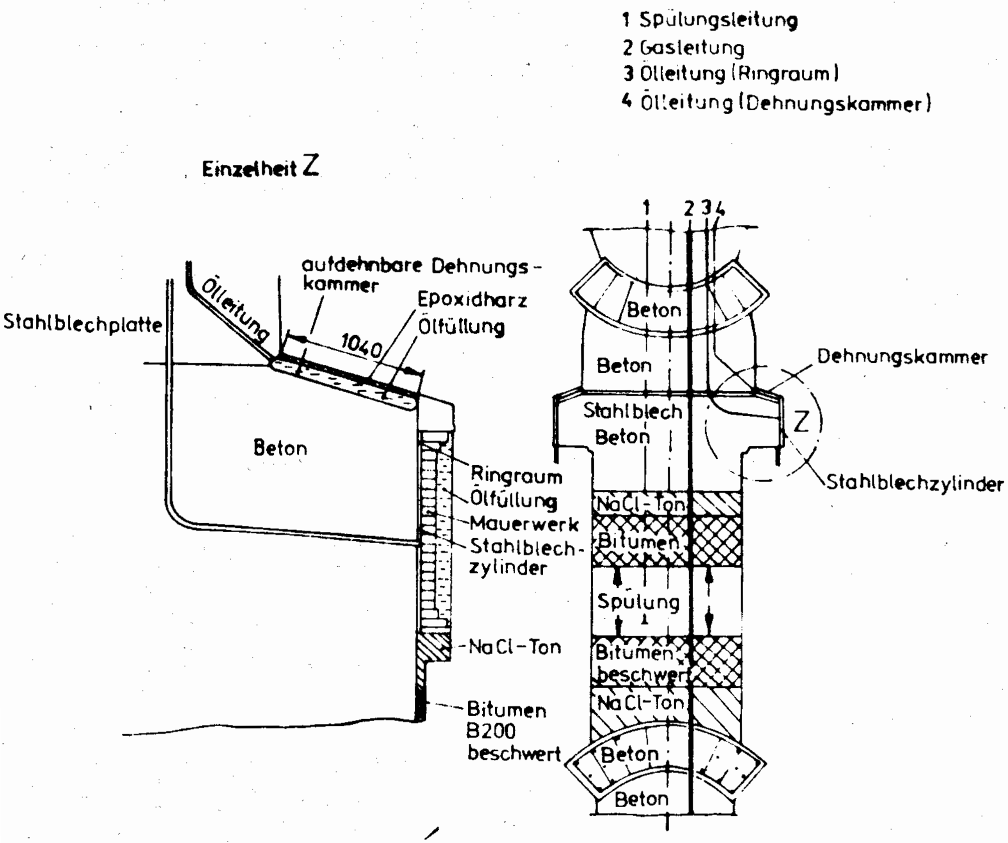
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2 Gasleitung
3 Ölleitung (Ringraum)
4 Ölleitung (Dehnungskammer)
Einzelheit Z
Stahlblechplatte
Ölleitung
aufdehnbare Dehnungs-kammer
1040
Epoxidharz
Ölfüllung
Beton
Ringraum
Ölfüllung
Mauerwerk
Stahlblech-zylinder
NaCl-Ton
Bitumen B200 beschwert
1
2
3
4
Beton
Beton
Stahlblech Beton
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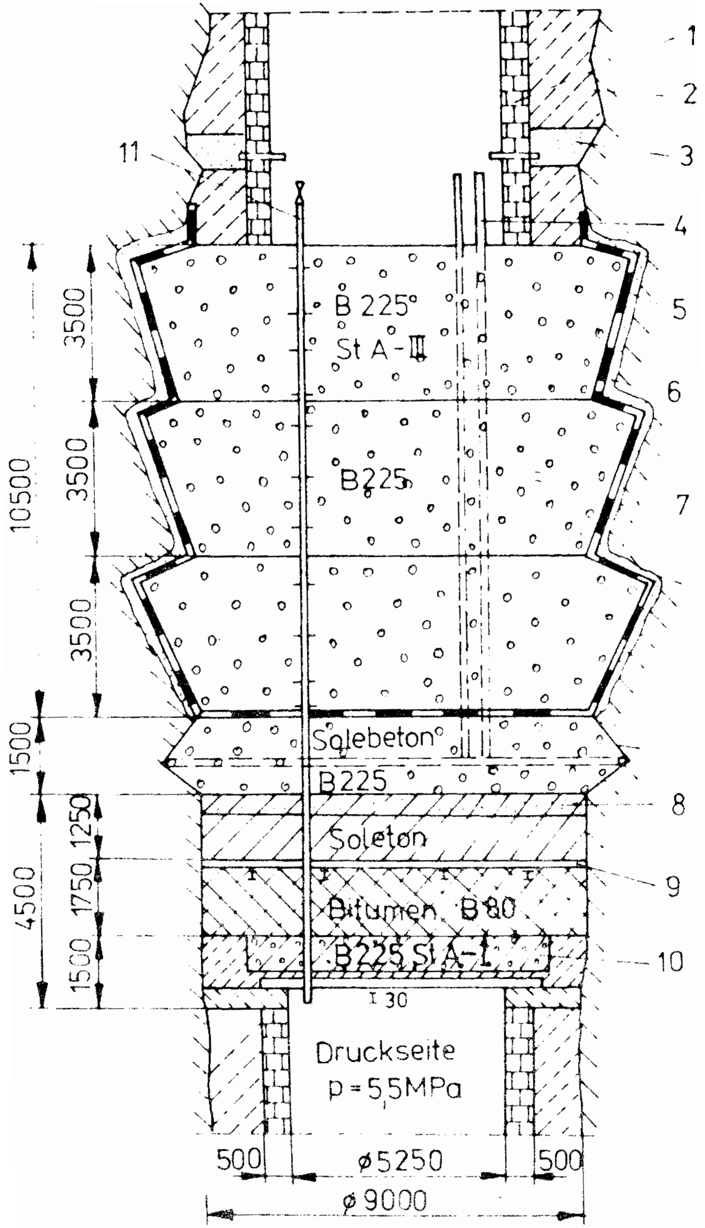
NaCl-Ton
Beton
Beton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B 225
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Solebeton
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Soleton
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Druckseite
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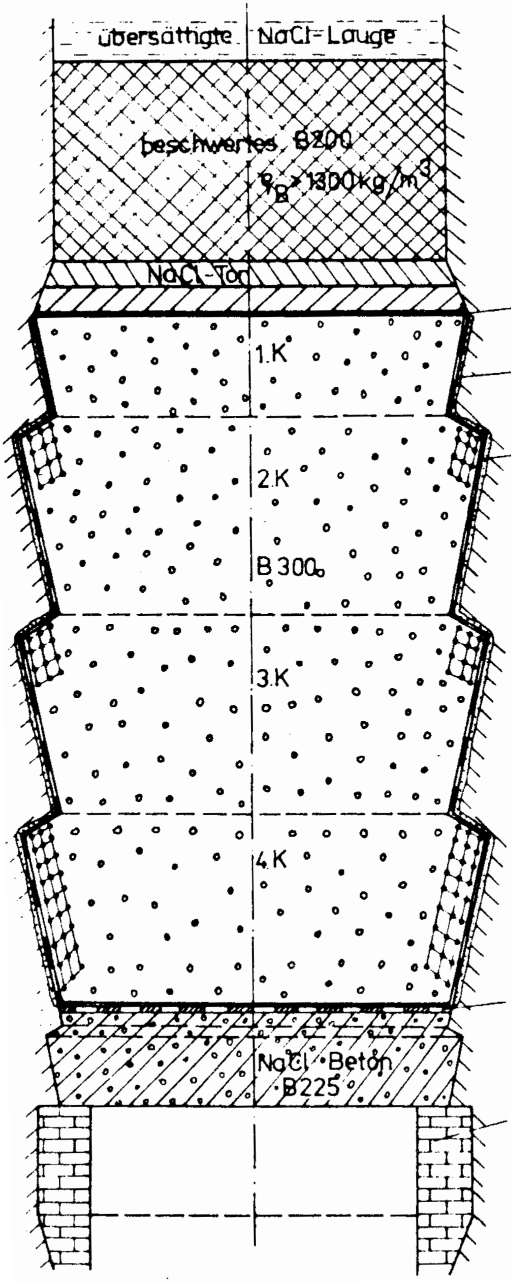
500
ø9000


übersättigte NaCl-Lauge
beschwertes B200
$\rho_B > 1300\ kg/m^3$
NaCl-Ton
1
2
3
4
5
1.K
2.K
B 300
3.K
4.K
NaCl-Beton
B225