The F.E.S. - Model and foundations for concrete dams.

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Summary

Mathematical models are a very useful tool to understand and to solve rock mechanics problems.

Due to the extremely broad variation of the physical and mechanical properties of the encountered rock and rock masses, no existing model may claim a general applicability for all the usual civil engineering problems.

The newly developed F.E.S.-Model (for Fissured, Elastic, Saturated Rock Mass) seems to be especially useful and well suited to study the rock foundation of concrete dams.

The model is explained and some applications are shown.

Introduction

Concrete dams require a rock foundation which offers a relatively high compressive strength as well as a sufficient rigidity in order to ensure the safety of the dam and to limit its deformations.

Up to the present time this fact led the designers to consider the rock foundation of concrete dams as an ideal elastic body and to use accordingly an elastic model to simulate its behaviour (e.g.) a Boussinesq-, Vogt- or USBR-Method or some elastic F.E.-Computations.

Doing so, one or more physical aspects of the problem were and are still disregarded:

— The rock mass being as a rule subdivided in blocks by discontinuity surfaces, no tension stresses can be sustained. Recently, this fact has been taken into consideration in using No-Tension F. E. - Models.

— However, even such models do not adequately take into consideration the fact that the opening of a joint in a rock mass is not solely due to tensile stresses.

— Indeed, the joint starts to open as soon as the compressive stresses decrease below a certain threshold.

— As a consequence, the modulus of deformability or of elasticity of the mass is not constant even in the compressive stress region.

— The rock mass surrounding the dam (and the reservoir) is subject to high and even very high internal water pressures in comparison with the total stresses. This fact plays an extremely important role which, as far as we know, was completely disregarded at least up to recent times.

— It is generally known — at least since the Malpasset disaster — that the permeability of the rock mass is influenced by the prevailing state of stress. However, even this aspect is not duly considered in many projects.

— The problem of grouting and draining a rock mass is generally solved (often in a wrong way) just on the base of some empirism or with a few of purely qualitative considerations. Appropriate tools to solve these problems were lacking.

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The F.E.S.-Model (for Fissured, Elastic, Saturated Rock Mass), which will be presented in the following, claims for itself to furnish the base for the study and the engineered solution of the problems just mentioned.

It has to be remembered that the aim of a model is first to enable us to get a better insight into the phenomena we are dealing with and only at a second stage to provide exact, directly usable numerical solutions to specific problems.

This second scope may be obtained obviously only if certain conditions are fulfilled, among which the necessity to know the exact value of a number of physical parameters needs to be stressed out.

On Models

Different ways may be followed in establishing a model.

A first way could consist in trying to approach as well as possible some observed or measured type of behaviour in combining a number of rheological well known, let us say classical, elements and in selecting accordingly a number of numerical parameters.

A different way, which was followed in establishing the F.E.S.-Model, consists in building up the model starting from known or measured properties of its components, mainly rock and water, and of its discontinuities. This procedure might be named a "synethetization" of the model. The validity and applicability of the model itself to a specific case can be checked at a second step by the use of some test procedure.

The extreme variability of the rock matrix as well as of the discontinuities, leads to a great number of different rock masses, and thereafter to a great number of different models which may be used in civil engineering projects on a case to case basis.

The F.E.S.-Model restricts itself to elastic fissured rock in presence of water, eventually under relatively high pressure. It maintains its validity up to the beginning of shear deformations. This type of rock mass can be considered to correspond to normal conditions for the foundation of concrete dams. So the main use and applicability of this model may lie, but surely not exclusively, in this field.

Establishing the F.E.S.-Model

A description of the F.E.S.-Model was already presented 9, 10 and a more detailed mathematical justification will be published in the near future, so that at this stage a short explanation of the principles followed may suffice.

1. Strain Stress Relationship

For the sake of simplicity we will study an isotropic elastic rock while also anisotropic rock could be taken into consideration in the same manner. The assumption of an elastic behaviour of the rock is justified as the working stresses on the dam foundation shall stay far below the compressive strength of the rock. As fissure we can name any kind of discontinuity of the rock mass.

While such a fissure may be considered to follow more or less a smooth surface at large scale, it will always show a clear rugosity at any shorter distance.

In spite of the fact that some geohydraulic model may have suggested it, a fissure is never completely open (that is defined by two exactly parallel surfaces at no contact) nor never completely closed (thus, in this case, it would be inexistvent from the practical viewpoint).
In fact a fissure is best represented, accordingly to Figure 1, by a series of zones where the two rock pieces are in contact and a single open zone (or more regions) where no contact exists.

This open zone may be completely or only partially filled with water. If the filling is total, we have to do with a saturated rock. If not, part of the fissure will be filled by air. As a rule in civil engineering works, the pressure of the air will be nil or very low*, so we may consider that in case of partial filling the behaviour of the rock mass will be the same as if there were no water. That means that we need, for our aim, to consider only saturated and dry rock masses while as a consequence of the stress changes a transition from virtually dry rock to saturated rock can take place.

To study the structural behaviour of such a fissure it is useful to introduce a parameter "x" defined as "degree of closure" of the fissure as shown at Figure 2.

Considering that the water in the fissure is under pressure, Figure 3 shows the equilibrium

* An exception may be encountered by caverns containing pressurized air.

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**Figure 2** — Degree of closure of a fissure.

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**Figure 3** — F.E.S. - Model for an elastic, fissured, saturated rock mass. Conditions of equilibrium for stresses and water pressure.
of the total stress "σ" with the neutral pressure "p" and the actual stresses "σ" at the contact points. Implicitly, one makes the assumption that the water pressure in the fissure is not related to a possible pore pressure in the rock itself.

Starting from the "fissure profile" and in computing the elastic deformations of the two rock blocks, the closing process of the fissure can be followed. The results are to be seen on Figure 4 where they are represented in a normalized scale for a given rock mass in function of the degree of closure x. The complete model is shown on Figure 5 for a set of identical fissures oriented perpendicularly to the direction of the principal compressive stress.

The graph of figure 5 shows the relationship between:

- total stress on the rock mass (σ in MPa)
- the strain for the rock mass (ε in %/o)
- the neutral water pressure p and
- the degree of closure of the fissures x

for a specific fissured rock mass.

Left of the line OC the fissures are completely open. Right of the same line they close progressively and are completely closed along the line AB.

The point A represents the total closing of the fissures at the lowest possible total stress in the dry rock mass. (σo, εo).

The line D-O-A-B shows the behaviour of the dry rock that is its "stress-strain" or "working line".

Each one of the similar lines drawn in the figure corresponds to a constant value of the water pressure p (as multiple of σo) acting in the fissures.

In the Figure 6 some lines of the complete model are stressed out for the sake of clarity.

Section a) shows how the 4 mentioned values relate together.

Section b) represents the stress-strain line for the dry rock mass. The section DO corresponds to the "no tension" criterion. From A to B the compression follows a linear elastic law with the elastic modulus E of the rock. The stretch OA corresponds to the elastic reversible but not linear closing of the fissures.

The value "a" represents the total opening of the uncompresssed fissures.

The natural and smooth way in which the transition from the elastic deformations to the "no tension" condition takes place, may be underlined.

Section c) of the same figure 6 refers to a rock mass with constant water content. From D to 0 there is no contact between the two faces of the fissure. From 0 to F the contact starts to build up. The volume of the fissures being bigger than the volume of water, the rock mass is not saturated and no water pressure exists. At point F the fissures are now completely filled with water, the rock mass is then saturated and the pressure in the water starts to increase (as long, of course, as the water can not escape). (The same stress-strain line would apply when the mass is grouted by a degree of closure equal to x = 0.6).

At section d) it may be seen how the change from a state of stress H to a state of stress I due to the closing of the fissures, and the change of the water pressure, may give the wrong impression of an elastic deformation with a low value modulus.

In many cases, but obviously not always, the stress-strain curve for dry rock at the stretch OA, where the fissures are partially open, can be quite well approximated through a power law as shown at Table 1. The entire relationship is also given in this table. The exponent "n" is the ra-
ratio of the total strain at complete closure to the theoretical linear elastic part of it. The non-linearity index \( n \) equals also the ratio of the modulus of elasticity to the secant modulus. The limit \( n = 1 \) corresponds to the pure linear elastic case also to an unfissured rock.

In handling with the F.E.S.-Model, four main directions assume a special meaning. They are stressed out in Figure 7 for a single point \( H \) of the graph.

Direction (1) is a compression of the rock mass by constant water content with an apparent modulus of elasticity identical to that of the rock itself. This is due to the practical incompressibility of the small volume of water enclosed in the fissures.

Direction (2) is a variation of the compressive stress by constant water pressure in the fissures. (Deformation with apparent low modulus.)

Direction (3) gives the deformation by constant total stress and a decreasing water volume and thus a decreasing of the water pressure in the fissures. This is the case of a drainage of the rock mass.

At the contrary, direction (4) represents the case of a simultaneous change of both the total stress and the water pressure by constant strain of the rock mass. This may happen e.g. in the horizontal direction when the rock mass is completely constrained and a change in the water pressure takes place.

In the same Figure 7 a "consolidation process" is shown as example which starts at point \( J \) with a rapid compression (1) followed by a slow drainage (3); both together are equivalent to a drained slow compression by constant interstitial water pressure (2).

The F.E.S.-Model allows many applications.

Figure 8 gives e.g. the influence of the number of fissures on the secant modulus of elasticity (point 0 to point A line in Figure 5) 2.3/.

In the previous pages the F.E.S.-Model was described as one-dimensional. It is easily understood that similar considerations and computations can be done in the 3-D space and that also various systems of fissures of different type, ruggedness, undulation and orientation can be investigated.
2. Hydraulics and F.E.S.-Model

Up to this point we took into consideration on the base of the F.E.S.-Model only a Hydrostatic equilibrium. As the flow of water through the fissures of the rock mass plays a very capital role in the civil engineering field, the hydrodynamics of the fissured rock will be looked at in the following.

The structural behaviour of the fissured rock mass is widely influenced by the rugosity of the fissures while the topology in their plane is not that important. On the contrary the hydrodynamical behaviour is fundamentally determined by the said topology.

Modelling means also schematization and simplification.

Among the various possible schemes, the one shown at Figure 9 was selected to idealize the configuration precedentely represented in Figure 1.

The dimension of the "islands" where the two faces are in contact depends, of course, on the state of compression across the fissure, and
Table 1

APPROXIMATION FOR THE NON LINEAR PART OF THE STRESS-STRAIN CURVE.

The complete closure of the fissures takes place at the point A defined by $\sigma_a$ and $\varepsilon_a$.

We call:

- $\sigma$: the actual total stress in the rock mass
- $\varepsilon$: the actual total strain of the rock mass
- $\sigma_a$: the total stress at complete closure ($x = 1$)
- $\varepsilon_a$: the strain at complete closure ($x = 1$)
- $E$: the modulus of elasticity of the rock.

Let be:

$$n = \frac{\varepsilon_a}{\sigma_a} \cdot \frac{E}{\varepsilon_o} \geq 1$$

the non-linearity index.

then the stress-strain relationship may be written:

$$\sigma = 0 \quad \text{as long as: } \varepsilon \leq 0$$

$$\sigma = \sigma_a \left( \frac{\varepsilon}{\varepsilon_o} \right)^n \quad \text{if } 0 \leq \varepsilon \leq \varepsilon_a$$

$$\sigma = \sigma_a + E \left( \varepsilon - \varepsilon_a \right) \quad \text{as soon as: } \varepsilon \leq \varepsilon_a$$

follows the $\sigma$-law selected. An example of such a law was displayed at figure 4. The higher the compressive stress is, the larger the islands will be.

It is relatively easy to compute the flow circulating in the net of channels around the islands we defined in using the normal methods of hydraulics. For the time being, a laminar flow was studied both for a Newtonian fluid like water and for a Bingham body like a stable water-cement grout mix. Some results are represented by the corresponding figures for selected single cases.

It has to be noted that while the "thickness" of the fissures, their degree of closing and their topology are of major importance, the scale itself of the topology in the plane has about no influence at all on the results.

Figure 10 shows the permeability of the rock mass, in the direction of the fissures and its variation as function of the degree of closure of the same, showing at the same time that the permeability decreases faster than the usual third power rule. This strong tightening up of the fissures with higher compressive stresses explains the low rate of water inflow in many deep underground excavations.

Figure 8 — Variation of the secant modulus (from first contact of the rock blocks to complete closure of the fissures) versus frequency of fissures of 0.6 mm thickness and 100 mm wave length by total lateral constraint.

Figure 7 — F.E.S.-Model. Typical directions of changes in the stress field.

1. Undrained increase of total stress.
2. Stress change by constant neutral pressure.
3. Drainage by constant total stress (also for grouting).
4. Stress and water pressure changes by constant strain.

Figure 7 — F.E.S.-Model. Typical directions of changes in the stress field.
It explains also the relatively low water pressure gradient around such opening where the rock was decompressed e.g. by blasting: such fissured masses work indeed mainly as a draining body.

The following Figure 11 gives the porosity due to a single system of fissures and its variation as function of the effective stress. The variation of the porosity versus stresses plays a major role in the behaviour of saturated rock masses especially in the foundation of concrete dams.

The tremendous difference between water and a stable grout mix in function of the degree of opening of the fissures as well as the dramatic decreasing of grout versus the degree of closure can be seen at Figure 12. This fact explains at least part of the difficulties encountered in trying to correlate the grout take in boreholes with the results of corresponding Lugeon tests. Also the need of high grout pressures, to open the joints and grout them, may be understood.

This short presentation of a few results of the hydrodynamics of the fissured rock on the base of the F.E.S.-Model allows to understand its usefulness in studying filtration through, and grouting of, fissured rock masses.

3. Special cases

The developments exposed in the former chapters were based on the hypothesis of a
thoroughly elastic behaviour of the rock blocks with a constant modulus. This need not be the case.

Some weathering and softening of the rock may have taken place in a thin layer along the two surfaces of the fissures. The influence of a weathering of variable thickness on the compressivity of a dry fissured mass is shown in Figure 13.

In a similar way the crushing of prominent asperities of the fissure topography under high stresses can be taken into consideration. This leads to an at least partial explanation of some apparently plastic deformation of the rock mass.

Applications of the F.E.S.-Model

The F.E.S.-Model was used to study a number of problems related with foundations of concrete dams. Few examples will be dealt with in the following pages.

1. The Zeuzier Dam

The F.E.S.-Model made it possible to understand the question of the settlements of rock masses due to their draining that is caused by the lowering of the ground water table.

A very spectacular example is the case of the Zeuzier arch dam in Switzerland where settlements of the valley as important as 15 cm took place as consequence of the drainage of the mountain caused by an investigation adit driven 400 m below the valley, 1.5 km aside of it.

These settlements caused a narrowing of the valley of more than 7 cm with obvious very important damages to the existing arch dam. The event can be briefly described by the three following figures.

Figure 14 relates the general geological situation under the dam, which is founded on Malm limestones. Below the Malm formation and protected by more or less impervious layers, one finds the marly limestones of the Dogger formation which bore a captive ground water. This underground reservoir was pierced and drained by the mentioned exploratory adit.

Figure 15 shows the very satisfactory agreement between measured and computed settlements while Figure 16 refers in the same way to the water flow discharging through the investigation adit.

2. Grouting and Hydrofracturing of Rock

The F.E.S.-Model was useful also in studying the problems related with the grouting and
Figure 12 — F.E.S.-Model. Grouting of a fissure; flow rate of stable water cement grout mix versus pressure gradient and degree of closure of the fissure.

Maximum aperture of the fissure 0.6 mm.
Relative cohesion of the mix 0.5 mm.
Viscosity of the mix $20.10^{-4}$ m$^2$/s.

the hydrofracturing of rock masses of this type both when using water or stable cohesive grout mixes. Among many other results, it could be shown that the use of high grout pressures can be harmful to the rock mass only when water or unstable mixes are used, while when injecting a stable mix even at a higher pressure, a progressive grouting of the fissures, but no unstable hydroleaching will take place.

Although obvious, it is sometimes necessary to remember that the grouting of a rock mass will unavoidably open somewhat the joints even if the grout pressure is far below the minimum stress component in the rock mass. This relationship is shown by the F.E.S.-Model (Figure 5).

To be mentioned is also the fact that a rock mass grouted under a certain stress pattern will assume a stress-strain curve similar to that shown in Figure 6c).

An additional conclusion, among others, that can be drawn from these facts is that to be tight a grout curtain must be grouted with the fissures open wider than they will be at operation time. This condition will impose higher grouting pressures than normally used in compliance to certain still imposed old specifications 4.8.9/.

3. Water Pressure and Deformation of the Dam Foundation

Under certain circumstances the traditional manner to compute the deformations of the foundation of the dam by assuming a linear elastic behaviour of the rock may not be adequate.

Figure 17 shows that at the upstream heel of an arch dam the filling of the reservoir produces a reduction of the vertical total stresses while the neutral water pressure will strongly increase.

Figure 13 — Stress-strain curves for a dry rock mass by various degrees of softening of the two rock faces of the fissures.

Fissures: wave height 0.6 mm, wave length 100 mm at 100 mm distance.
Weathering of the rock faces: reduction of the modulus of elasticity by 10 times on a depth of 0.05.1 and .2 mm.
Figure 14 — Zeuzier Dam.
Captive ground water.
M = Malm, D = Dogger,
CC = captive ground water,
T = investigation adit,
D = arch dam.

Figure 15 — Zeuzier dam. Settlemens versus time. Measured and computed values.

Figure 16 — Zeuzier Dam.
Drained water flow versus time. Measured and computed values.
The combination of these two influences leads to an important expansion of the rock mass thus to an apparently reduced modulus of elasticity when compared with the corresponding dry rock. As a consequence possibly computed tensile stress in the concrete at the heel of the dam will not appear.

As the permeability of the rock mass depends on the difference between total stress and water pressure, the permeability of the rock mass will change continuously during the impounding of the reservoir. This will happen in a different manner from point to point of the foundation. As a result the uplift distribution under the dam will assume any shape but a linear one.

4. Apparent Viscosity of an Elastic Rock Mass

The porosity and the permeability of the rock mass depend both on the effective stress in the fissures (as difference between the total stress and the water pressure).

It is easy to understand that the viscosity of the water is in reality the reason for an apparent viscous behaviour of elastic rock masses of the type we discussed here.

Final Comment

For the time being no one of the existing models may claim a wholly satisfactory applicability to any type of rock mass.

The F.E.S.-Model seems however to be particularly well suited to deal with relatively strong, approximately elastic rocks which are jointed and fissured and submitted to relatively high interstitial water pressures.

It is exactly this kind of rock and this kind of problems that one should encounter at the foundation of concrete dams.
References

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