Optimum characteristic compressive strength for cmds (case study: dasht-e-palang dam)

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Abstract

Using Cemented Material Dams (CMD) is advantageous in a prospect that it allows construction of concrete dams on almost every foundation rocks including weak ones. For a successful design of this type of dams on weak rocks, more consideration is needed. Since stresses in dam body are proportional to modulus of rock and dam body, determining an optimum compressive strength (f'_c) for material of dam body (named hardfill) is a major concern. Choosing low f'_c means inadequate safety factor for stresses while choosing high f'_c means high cost and thermal challenges for dam body. Stresses are dependent on dam and foundation's modulus of deformations and modulus of deformation itself depends on compressive strength of material, which in turn produces a loop that should be solved correctly in an optimum way. In this paper, a probabilistic approach to determine optimum and safe f'_c is proposed. Hardfill material of Dasht-e-Palang dam is chosen as a case study and analyzed by this method to obtain an optimum compressive strength of hardfill. An applicable graph for CMD design with arbitrary height and symmetrical slopes is presented in this paper.

Keywords: CMD, Hardfill, FSHD, Optimum Cement, Probabilistic.

1. INTRODUCTION

Cemented Material Dam (CMD) is a type of Gravity Dam which includes Faced Symmetrical Hardfill Dam (FSHD), Cemented Sand and Gravel (CSG), Rockfill Concrete (RFC), Cemented Soil Dam (CSD) etc. A main branch of CMD is FSHD/CSG/CSGR. Western countries hardfill, Japanese CSG and Chinese CSGR are variations of the same basic concept. Dam body material of these three types is called "Hardfill". FSHD and CSG are very similar to each other. All mentioned types have been constructed and widely welcomed by the engineers all over the world. For the first time in IRAN, some CMD's are under construction, which are designed, and now are under supervision of construction by ABFAN Consulting Engineers Co.

As ICOLD anticipated in bulletin No. 117 dated 2000, this generation of Gravity dams are "the future dams" especially in under-developed countries. In IRAN, suitable dam sites with good foundation rock and good borrow materials have been selected for the previous hundreds of dams, and now the country faces severe conditions for selecting dam sites. CMD design concept, allows having a rigid (or gravity) dam body on almost every rock foundation even on very weak rocks and with low specific aggregates used in the dam.

Nowadays there is common understanding on how to distinguish hardfill from lean RCC. In CMD committee meeting at Johannesburg 2016, the main features of hardfill dams agreed as: "No tension governing in design, Quasi symmetrical shape, Range of UCS from 3 to 10 MPa, Sum of slope greater than one and Watertight upstream facing".

It is noted frequently that these kind of dams (in comparison with conventional RCC dams) have less challenges in design and construction, but "CMD on weak foundation" still needs more considerations for a successful design. For example, the "variations" of compressive strength of hardfill is more than RCC projects because the aggregates are not processed like RCC projects. It results in various and unknown value of modulus of elasticity of hardfill which results in unknown stress generation in structure. Determining characteristic compressive strength for hardfill dams is very important because it plays the main role in total cement usage. In this paper, a probabilistic approach to determine optimum compressive strength (and in other words, it may be used to calculate the optimum cement usage) for this type of dam is proposed.

2. STRESS ANALYSIS

At the first step of designing a gravity dam, stability is checked and the optimum geometry of dam is determined. Stress analysis is conducted in the second step. All stresses in dam body, considering various load combinations, should be compared to allowable stresses. For each value of E_c or $E_{hardfill}$ (modulus of deformation for the dam body), a new stress distribution with respect to the load combination is obtained (figure 1.a). Note that stress values depend on ratio of $E_{hardfill}$ to $E_{rock\ foundation}$, but for simplicity we will consider $E_{rock\ foundation}$ values equal to 1 GPa.

By performing finite element analysis for different values of $E_{hardfill}$ and finding the highest compressive stress generated in the structure (or transformed tensile stress to compressive stress) a fitted curve for input $E_{hardfill}$ against maximum compressive strengths can plotted (figure 1.b).

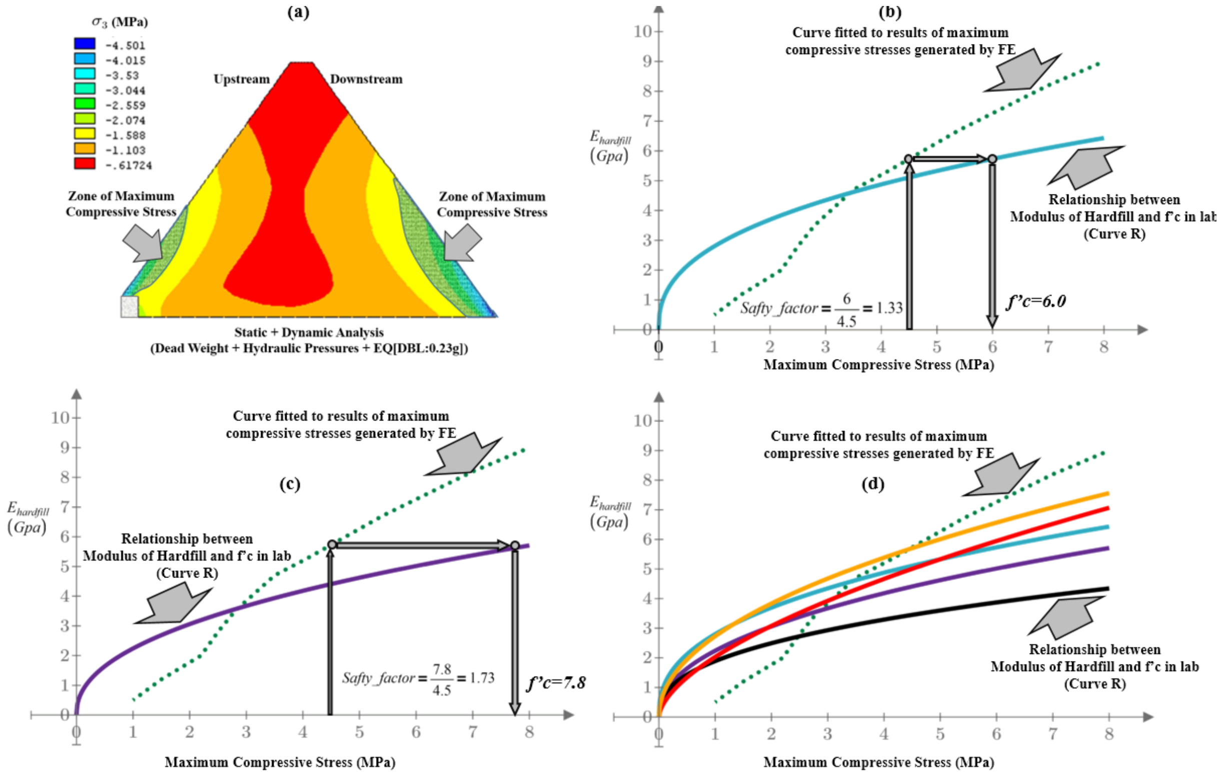


Figure 1. Modulus of deformation vs. compressive strength

Maximum required strength is the higher value between f'_t and f'_c where:
f'_t: Maximum required hardfill strength to withstand the tensile stress
f'_c: Maximum required hardfill strength to withstand the compressive stress
So it is needed to find the relationship between f'_t and f'_c of the hardfill material. Comparison between USBR formula and other practical references (Conrad 2006 [1]) shows a meaningful correlation between f't and f'c which is: $f'_t = 0.2 \cdot f'^{\,0.8}_c$ (units in Mpa) (1)

On the other hand, each f'_c of hardfill material will produce an initially unknown $E_{hardfill}$. Assuming that this relationship is known as curve R in the figure 1. b, it is clear that intersection of these two curves may be the desired f'_c. Strengths lower than this value are not permitted and strengths higher than this value are uneconomical and will produce more heat and thus to increase potential for cracks in the structure. In addition, it should be noted that safety factors should be considered for stresses. For example, to determine the characteristic strength of hardfill, if a dynamic analysis is performed (using an unusual earthquake load), maximum compression stresses should be multiplied by a factor of 1.54. In this manner, a non-linear equation should be solved to find the optimum f'_c (figures 1.b and 1.c) that meets all the requirements for allowable stresses. For example, as shown in figure 1, when there is no fixed approved curve for relationship between E_c and f'_c of hardfill, each sample of hardfill material may generate a different curve, which in turn yields a different stress safety factor. The curve shown in figure 1.b has a safety factor of 1.33 which is lower than allowable safety factor (1.54) and the curve shown in figure 1.c has a safety factor of 1.73 which is upper than allowable safety factor. The challenge is how to find a minimum f'_c for hardfill that satisfies allowable safety factors?

3. PROBABILISTIC APPROACH

In this paper, it will be shown that, probabilistic approach is a proper way to find a minimum f'$_c$ that satisfies allowable stresses for hardfill materials. Followings are considered to be affecting the results of this analysis:

- Relationship between f'$_c$ and E$_c$ in Lab tests
- Estimating modulus of "hardfill mass" of dam body
- Probabilistic parameters of rock foundation (mainly E of rock)

The formulation of probabilistic functions are as follows:

$$E_{mass} = f^{*}\left(f'_c, E_{rock}, \frac{E_m}{E_i}\right) \qquad (2)$$

$$\sigma_{max} = g^{*}(E_{mass}) = g^{*}\left(f^{*}\left(f'_c, E_{rock}, \frac{E_m}{E_i}\right)\right) \qquad (3)$$

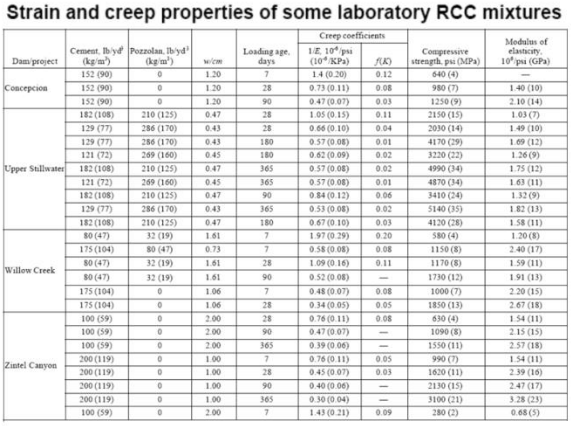
$$\frac{f'_{c_i}}{\sigma_{max_i}} = Safety\_factor_i \qquad (4)$$

Further explanation on each item is presented in next sections.

4. RELATIONSHIP BETWEEN (F'C) AND (EC) IN LAB TESTS

Using Schrader's [2] data (figure 2 right) for f'$_c$ lower than 10 MPa, following relation to obtain the stress-strain curve for the hardfill material can drive:

$$E_c = 2700 \cdot f'_c{}^{0.5} \quad \text{(units in Mpa)} \qquad (5)$$



Strain and creep properties of some laboratory RCC mixtures

Dam/project	Cement, lb/yd³ (kg/m³)	Pozzolan, lb/yd³ (kg/m³)	w/cm	Loading age, days	Creep coefficients: 1/E, 10^{-6}/psi (10^{-6}/KPa)	Creep coefficients: f(K)	Compressive strength, psi (MPa)	Modulus of elasticity, 10^6/psi (GPa)
Concepcion	152 (90)	0	1.20	7	1.4 (0.20)	0.12	640 (4)	—
	152 (90)	0	1.20	28	0.73 (0.11)	0.08	980 (7)	1.40 (10)
	152 (90)	0	1.20	90	0.47 (0.07)	0.03	1250 (9)	2.10 (14)
Upper Stillwater	182 (108)	210 (125)	0.47	28	1.05 (0.15)	0.11	2150 (15)	1.03 (7)
	129 (77)	286 (170)	0.43	28	0.66 (0.10)	0.04	2030 (14)	1.49 (10)
	129 (77)	286 (170)	0.43	180	0.57 (0.08)	0.01	4170 (29)	1.69 (12)
	121 (72)	269 (160)	0.45	180	0.62 (0.09)	0.02	3220 (22)	1.26 (9)
	182 (108)	210 (125)	0.47	365	0.57 (0.08)	0.02	4990 (34)	1.75 (12)
	121 (72)	269 (160)	0.45	365	0.57 (0.08)	0.01	4870 (34)	1.63 (11)
	182 (108)	210 (125)	0.47	90	0.84 (0.12)	0.06	3410 (24)	1.32 (9)
	129 (77)	286 (170)	0.43	365	0.53 (0.08)	0.02	5140 (35)	1.82 (13)
	182 (108)	210 (125)	0.47	180	0.67 (0.10)	0.03	4120 (28)	1.58 (11)
Willow Creek	80 (47)	32 (19)	1.61	7	1.97 (0.29)	0.20	580 (4)	1.20 (8)
	175 (104)	80 (47)	0.73	7	0.58 (0.08)	0.08	1150 (8)	2.40 (17)
	80 (47)	32 (19)	1.61	28	1.09 (0.16)	0.11	1170 (8)	1.59 (11)
	80 (47)	32 (19)	1.61	90	0.52 (0.08)	—	1730 (12)	1.91 (13)
	175 (104)	0	1.06	7	0.48 (0.07)	0.08	1000 (7)	2.20 (15)
	175 (104)	0	1.06	28	0.34 (0.05)	0.05	1850 (13)	2.67 (18)
Zintel Canyon	100 (59)	0	2.00	28	0.76 (0.11)	0.08	630 (4)	1.54 (11)
	100 (59)	0	2.00	90	0.47 (0.07)	—	1090 (8)	2.15 (15)
	100 (59)	0	2.00	365	0.39 (0.06)	—	1550 (11)	2.57 (18)
	200 (119)	0	1.00	7	0.76 (0.11)	0.05	990 (7)	1.54 (11)
	200 (119)	0	1.00	28	0.45 (0.07)	0.03	1620 (11)	2.39 (16)
	200 (119)	0	1.00	90	0.40 (0.06)	—	2130 (15)	2.47 (17)
	200 (119)	0	1.00	365	0.30 (0.04)	—	3100 (21)	3.28 (23)
	100 (59)	0	2.00	7	1.43 (0.21)	0.09	280 (2)	0.68 (5)

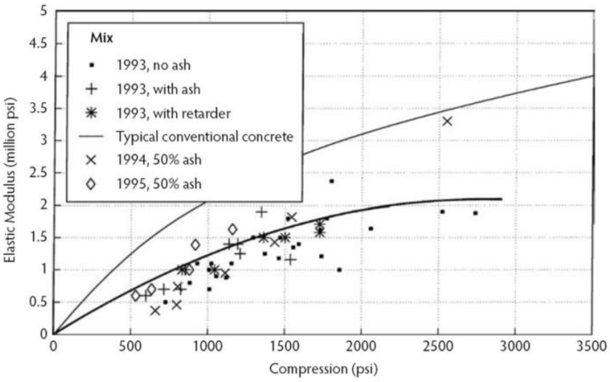


Figure 2. Elastic modulus at 25% of ultimate load vs. compression (left : ACI207 , right : Schrader [2])

It can be seen from figure 2 (right side) that conformity is poor. In addition, some samples of Kahir dam (the first CMD in Iran) have been used. The Kahir relationship is in the form of power regression but with low regression coefficient.

Using ACI records [3] gives higher amount of modulus, which could be stated by:

$$E_c = 4700 \cdot f'_c{}^{0.5} \quad \text{(units in Mpa)} \qquad (6)$$

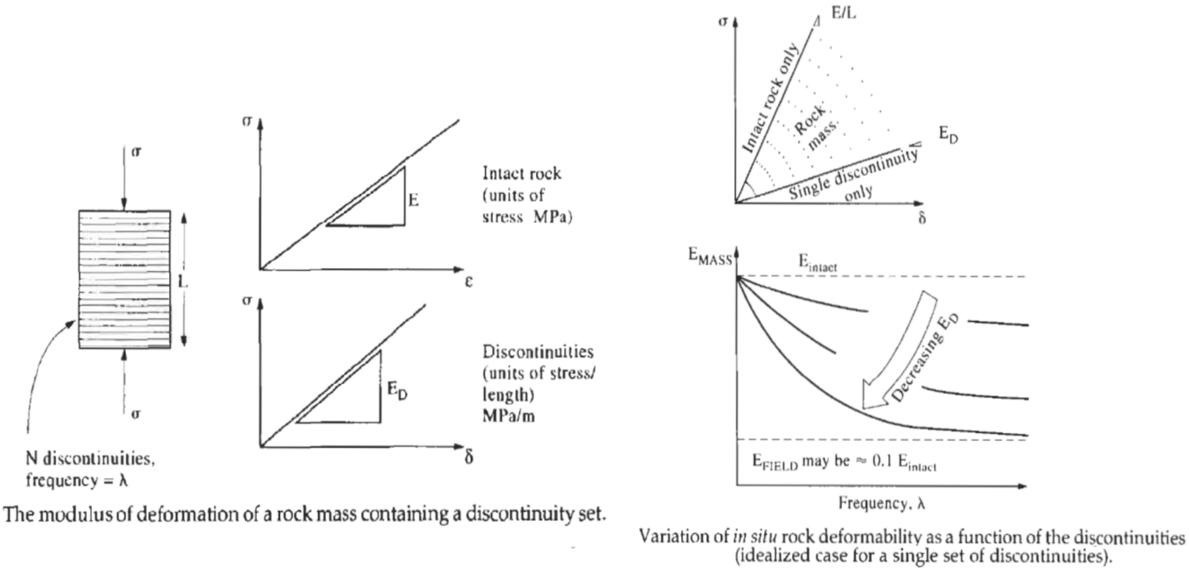
Therefore, probabilistic formulation can be assumed in the form of the following:

$$E_c := a \cdot f'c^{b} \qquad (7)$$

If there were enough tests that relates E to f'c, we could stablish a probabilistic formula instead of fitting curve with low coefficient. Otherwise we may assume "a" as a random normal distribution with mean value equal to 3.5 and standard deviation value equal to 0.5 and "b" as a random normal distribution with mean value equal to 0.5 and standard deviation value equal to 0.05. These assumptions may cover the ACI and the Schrader formula with a probability of 95 percent.

5. PROPOSING A NEW METHOD FOR ESTIMATING MODULUS OF HARDFILL MASS

In hardfill dams, the modulus of mass body is lower than intact sample and it plays the main role in calculation of stress and its distribution. The authors of this paper propose to use rock mechanics approach for estimating modulus of hardfill bodies. In rock mechanics, there is a wide range of studies on how to relate intact modulus to mass modulus [4]. The basic theory is illustrated in figure 3. Most of the methods, apply a reduction factor to Ei (intact modulus) to obtain the Em (mass modulus).



The modulus of deformation of a rock mass containing a discontinuity set.

Variation of *in situ* rock deformability as a function of the discontinuities (idealized case for a single set of discontinuities).

Figure 3. Variation of in situ deformability as a function of discountinuities

A simple relation, proposed by Bieniawski [5], relates the two moduli using RQD as follows:

$$E_m := E_i \cdot \left(10^{.0186 \cdot RQD - 1.91}\right) \quad (8)$$

Figure 4. Core samples of Kahir dam

Horizontal joints between layers of CMD are very weak (because we have no bedding mortar) and therefore RQD values are below 100%. For Kahir project, RQD of cores has a mean value of 85% (see figure 4 as an example). In this paper, a uniform random distribution of RQD between 70% to 100% for hardfill is assumed (see figure 5) and CQD term is used instead of RQD. Another method is relating the reduction factor to RMR, which in layered dam bodies relates it to RQD again.

$$\frac{E_m}{E_i} = \frac{1}{100} \cdot \left(0.0028 \cdot RMR^2 + 0.9^{\frac{RMR}{22.82}}\right) \qquad (9)$$

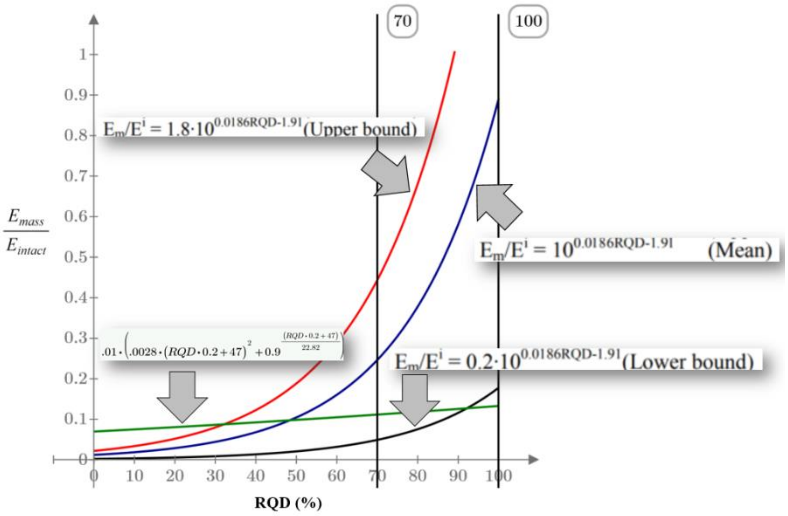
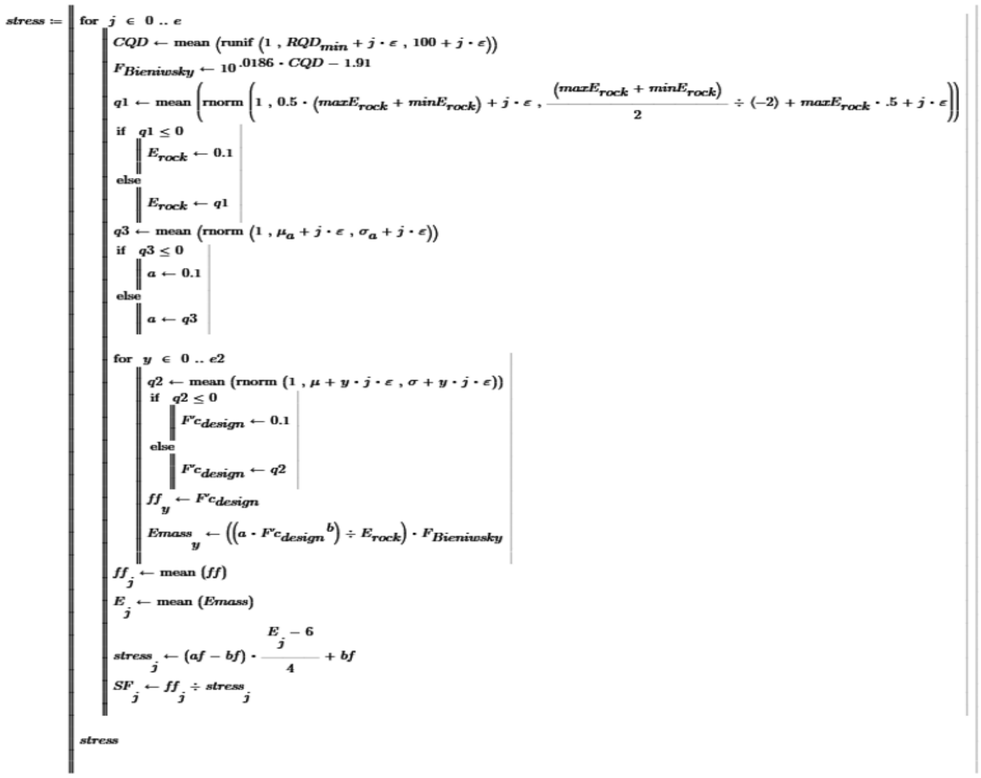


Figure 5. Upper bound, mead and lower bound of Bieniawski realtionship

6. USING MATHCAD TO PERFORM PROBABILISTIC ANALYSIS

Mathcad is an engineering math software that allows user to perform, analyze, and share mathematical calculations. Using Mathcad software for solving probabilistic equation, a simple written code should solve (a sample code is shown in figure 6). In this figure, “e” is the iteration, “af” and “bf” are the factors for fitted line in figure 1.a, which is derived from FEM analyses. The output of this code is density distribution of stress safety factors. To find the optimum f'_c, we should change f’c as an input to find such a distribution of stress safety factors that has only 20% failures (accepted for many gravity dams). For example, if the minimum stress safety factor is 1.54 (for unusual earthquake load), we should change f’c as an input until the integral of distribution of stress safety factor curve is less than 20% (or any other value that is acceptable by designer).



```
stress := for j ∈ 0 .. ε
              CQD ← mean (runif (1 , RQD_min + j · ε , 100 + j · ε))
              F_Bieniwsky ← 10^(.0186 · CQD − 1.91)
              q1 ← mean (rnorm (1 , 0.5 · (maxE_rock + minE_rock) + j · ε , (maxE_rock + minE_rock)/2 ÷ (−2) + maxE_rock · .5 + j · ε))
              if  q1 ≤ 0
                  E_rock ← 0.1
              else
                  E_rock ← q1
              q3 ← mean (rnorm (1 , μ_a + j · ε , σ_a + j · ε))
              if  q3 ≤ 0
                  a ← 0.1
              else
                  a ← q3

              for  y ∈ 0 .. e2
                  q2 ← mean (rnorm (1 , μ + y · j · ε , σ + y · j · ε))
                  if  q2 ≤ 0
                      F'c_design ← 0.1
                  else
                      F'c_design ← q2
                  ff_y ← F'c_design
                  Emass_y ← ((a · F'c_design^b) ÷ E_rock) · F_Bieniwsky
              ff_j ← mean (ff)
              E_j ← mean (Emass)
              stress_j ← (af − bf) · (E_j − 6)/4 + bf
              SF_j ← ff_j ÷ stress_j
          stress
```

Figure 6. A sample code to solving the probabilistic equation

7. CASE STUDY: DASHT-E-PALANG DAM

Dasht-e-Palang dam is under construction in Bushehr province on a river with the same name. Project objectives are providing drinking, industrial and agriculture water. The dam is a combination of gravity and earthfill dam (which the main part is CMD) with following specifications [6]:

- Maximum height: 56m
- CMD part crest length: 350m   Earthfill crest length: 680m
- CMD part crest width: 4m   Earthfill crest width: 8m
- Upstream and downstream slope of dam body: 0.7 h/ 1.0 v
- Hardfill volume: 540,000m3   CVC volume: 150,000m3
- Earthfill volume: 1,000,000m3

Design parameters of DASHT-E-PALANG dam are as follows:

Foundation rock modulus: 0.5-1.0 GPa (a normal probabilistic distribution for this parameter is used in the analysis)

Shear strength parameters of foundation: Ø=29°, C=0.14 MPa

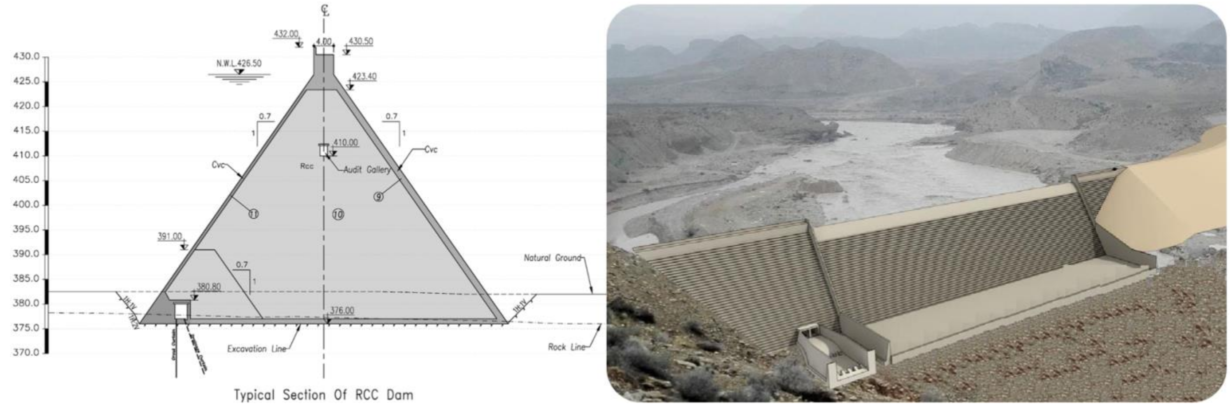


Figure 7. Dasht-e-Palang Dam (a combination of CMD & Earthfill)

Analysis, using probabilistic assumed and real data, will give us the following graphs (Figure 8). By trial and error, we will find that assuming a normal distribution for f’c of samples in Dasht-e-Palang dam, with a mean of 7 MPa (known as fcr) and a coefficient of variations of 30% (which means a standard deviation of 2.1 MPa) we will have a f’c equal to 7-0.824*2.1=5.2 MPa. After performing tests (to determining E in the lab), it is possible to estimate f'_c better. Note that after construction of dam body, it is possible to use the real distribution of compressive strengths to evaluate the safety of structure.

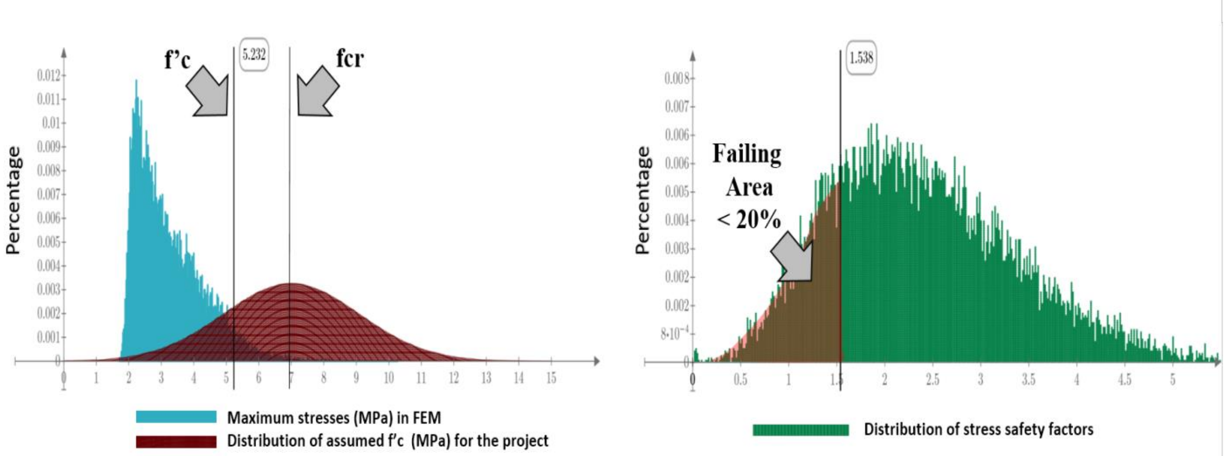


Figure 8. Dasht-e-Palang dam probabilistic analysis results

8. APPLICABLE GRAPHS

Using the method described here, a probabilistic relation between modulus of foundation and optimum f'_c can be acquired for each shape of the dam and following graphs (Figure 9) may produce.

On how to use the graphs, consider Dasht-e-Palang dam for example. If modulus of foundation rock is 0.8 GPa with dam slopes equal to 0.7h:1.0v, a characteristic compressive strength not less than 5.5 MPa must be selected.

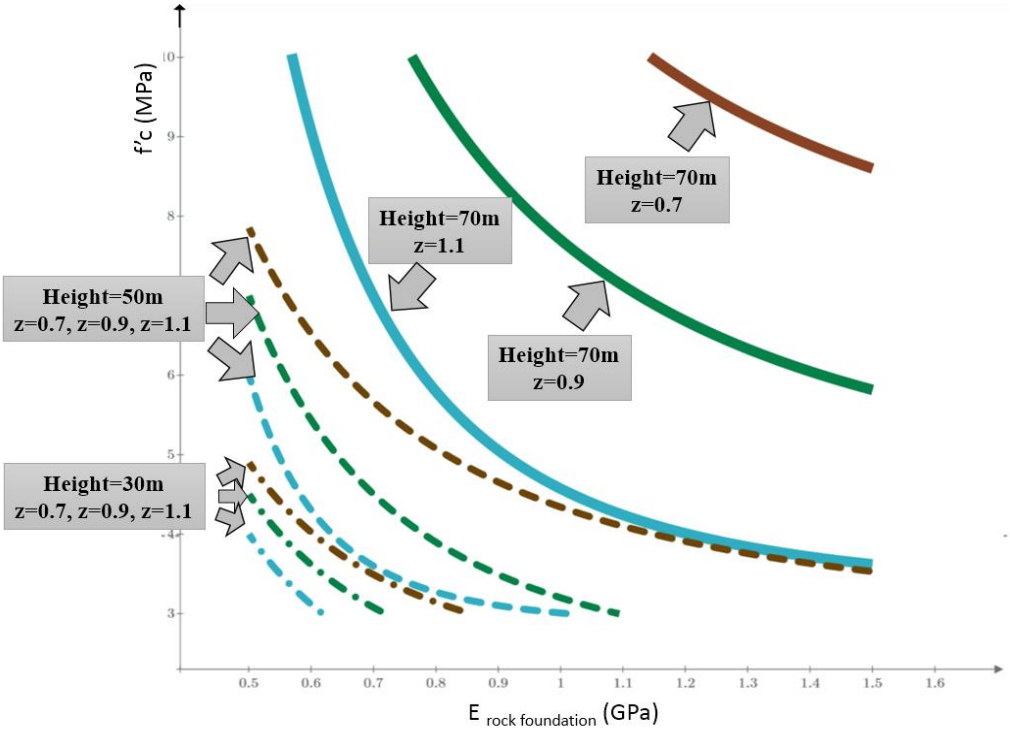


Figure 9. Relationship between modulus of foundation and optimum f'c of Hardfill

9. CONCLUSIONS

There is not a reliable deterministic relationship between modulus of hardfill and f'$_c$. This relationship has an immense role in determining optimum f'c for each project. Using probabilistic method on estimating modulus of samples with various f'$_c$, and estimating the "mass modulus" of dam body by methods proposed in rock mechanics and establishing a probabilistic distribution on rock modulus of deformation (if needed) a probabilistic distribution graph of stress safety factors can be produced. Using said graph, calculating the characteristic compressive strength of hardfill material with a desired reliability is possible. An applicable graph for designers, which shows the relationship between E$_{rock}$ (modulus of deformation of foundation) and optimum f'$_c$ (of hardfill of many CMD geometries), is presented in this paper.

10. ACKNOWLEDGMENT

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