ABSTRACT

With rapid population growth and accelerating economic development, much of the world’s WATER which requires urgent attention to ensure sustainable use. Nowadays, Concrete Faced Rockfill Dam (CFRD) is preferred among dam consultant due to its advantages. They are designed to withstand all applied loads; namely gravity load due to its massive weight and hydrostatic load due to water thrust from the reservoir. Bakun CFRD, which ranks as the second highest CFRD in the world when completed, is analyzed to its safety due to both loads mentioned earlier by using Finite Element Method. 2-D plane strain finite element analysis of non-linear Duncan-Chang hyperbolic Model which formulated by Duncan and Chang is used to study the structural response of the dam in respect to the deformation and stresses of Main dam of Bakun’s CFRD project. Dead-Birth-Ghost element technique was used to simulate sequences of construction of the dam as well as during reservoir fillings. The comparison of rigid and flexible foundation on the behaviour of the dam was discussed. The maximum and minimum principal stresses are the maximum and minimum possible values of the normal stresses. The maximum principal stress controls brittle fracture. In the finite element modeling the concrete slab on the upstream was represented through six-noded element, while the interface characteristic between dam body and concrete slab was modeled using interface element. The maximum settlement and stresses of the cross section was founded and the distribution of them were discussed and tabulated in form of contours.

Keyword: CFRD dams, non-linear, finite element analysis, water fillings

1. INTRODUCTION

Malaysia, which comprises Peninsular Malaysia, Sabah and Sarawak, is located between latitudes 1° and 7° North and longitudes 100° and 119° East which covers a total land area of over 330,000 km². With rapid population growth and accelerating economic development, much
of the natural resources are being depleted at an unsustainable rate. One of these resources is WATER which requires urgent attention to ensure sustainable use.

In this paper, Bakun Dam which is the second biggest Concrete Faced Concrete Dam (CFRD) in the world when completed behind Shuibuya Dam in China is analyzed to its safety by using finite element method. Dam structure often store huge quantity of water at great potential energy and if in the case of failure does pose an imminent threat to population and property downstream. There are a few factors need to be taken care of when designing a dam, i.e. safety, economy, efficiency and appearance. Safety and economy are factors that contradict to each other; however, we may design an economical dam without sacrificing the safety of the dam.

Dams are designed to withstand all applied loads, e.g. gravity load, hydrostatic, hydrodynamic pressures etc. The biggest loads on dam are the gravity load due to its massive self weight and also earthquake loads. The accuracy of the estimation of dam safety under static and earthquake (dynamic) and the design work require a good understanding of structural response of dam under both cases. As far as the design aspect concerns, static load and dynamic load are contradicts as in static we need to design the stiffest structure, however, in dynamic it is required to design the structure most flexible. Therefore, the engineers should be aware of both criteria and fulfills to its optimum dam design.

Since dams are considered to be as mega projects, and infrastructures for any nation, hence, many international organization (International and National Commission on Large Dams (ICOLDS)), are involved in the documentation data of the concrete faced rockfill dam which was designed and constructed. After the evaluation of their implementations and operations, the legislation and guidelines on dam safety are issued, accordingly, to be followed by the owner of dams, consultants and construction dam industries. CFRD is being recognized as one of the best choices among the dam consultants and engineers for its advantages.

2. PREVIOUS FINDINGS

There are methods available for prediction of deformations during construction, but they are limited in number. Development of these methods has probably been curtailed by the availability of finite element methods in the last 30 to 40 years, their relative ease of use to model embankment construction and improvements in constitutive relationships to model the material compressibility and deformation behaviour. In addition, the complexity of stress and deformation behaviour during construction, particularly for zoned embankments, makes assessment by simple empirical methods difficult.

Poulos et al (1972) developed charts for estimation of stresses and vertical and horizontal deformations during construction based on elastic solution for a homogeneous embankment on a rigid foundation. The methods provide a quick and simple means of estimating deformations. ICOLD (1993) derived a general equation for the vertical strain of rockfill in terms of vertical stress, rockfill modulus and creep strain parameters based on the assumption of a linear relationship between stress and strain of coarse rockfill and non-linear relationship between strain and time. Derivation are given (refer ICOLD 1993) for the settlement at a specific elevation and period of time start of construction, settlement at end of construction and settlement post construction.

Most of the earliest CFRD researchers introduced one-shot loadings in their analysis. From the analysis of one-shot loading, we found that maximum vertical displacement occurs at the crest of the dam. This is much contrary as vertical displacement should occur at the foundation level due to phenomena called “overburden”. Noorzaei et al. (1999), developed finite element program that it can simulate the sequence of construction of the earthen and rockfill dam, which is done by the real and ghost technique that complete body of the dam has been discretized and
the stages of construction has been represented by real and ghost elements. The result obtained are most simulate to the actual conditions.

Xu (2000), used three dimensional non-linear finite element method developed computer software called SDAP3D in the analysis of stress and deformation properties of Wuluwati CFRD, in China with 138 m. Height and 365 m lengths, with upstream slopes 1:1.6 and downstream slopes 1:1.5 the program uses Duncan et al (1980), nonlinear elastic model. This software dealt with the interaction between the concrete slab and the rockfill materials. Maximum principal stresses occurred in the bottom of the dam body at the end of sequence of construction and the value of major principal stress is 1.8 MPa, while the minor one is 0.6 MPa. After the impounding the maximum principal stress increased to 2.0 MPa and the minor principal stress to 0.8 MPa.

Xingzheng et al. (2002), use 3-D finite element analysis to evaluate stresses and deformation of Yutiao CFRD during construction and reservoir filling stage. During construction, Yutiao CFRD shows its maximum major principal stresses of 1.78 MPa which occurs at the bottom of the dam while for the case after reservoir fillings, it gave its maximum value of 1.87 MPa. On the other hand, maximum minor principal stresses shows its value of 0.74 MPa occurs at the bottom of the dam during the construction and 0.72 MPa after the reservoir fillings.

Chen et al. (2000) was used a nonlinear elastic developed hyperbolic (Duncan, 1984), E-B model to analyze Shuibuya (233 m) concrete face rockfill. The maximum horizontal deformation of the dam is 0.20 m towards the upstream at the end of construction while it is 0.67 m at the end of reservoir filling and its movement towards the downstream. The maximum vertical deformation occurred at the 2/3 dam height with value 1.67m. at end of construction and 0.77 m at the end of reservoir filling. The maximum principle major and minor stresses is 3.18 MPa and 1.02 MPa, respectively, at the end of construction, and, 3.52 MPa and 1.27 MPa at the end of reservoir filling. Gao et al. (2001), in this analysis a nonlinear constitutive law of uncoupled K-G model was used in the calculation of high CFRD. In this case, the stress path is very complicated since the filling process of the dam is divided into several stages during construction. The basic formula of the model and the incremental regression method for obtaining the parameters are introduced. He reported that at the end of reservoir filling, major and minor principal stresses of Shuibuya Dam is 4.07 MPa and 1.33 MPa respectively.

Realistic simulation of the stress-strain characteristics of the soil (which is non-linear) is the principal factor governing the accuracy of finite element analysis of embankments. As studied by Boughton, he showed that the linear analysis of a rockfill dam, using a conventional finite element program and constant values of elastic properties for the rockfill, gave areas of tensile stress in the rockfill, independent of the value of elastic modulus employed. As the rockfill cannot sustain tensions, this is clearly not applicable. Subsequent analysis, simulating nonlinear behaviour of rockfill, resulted in elimination of the impossible tensile stress (Duncan, 1972). The hyperbolic model is one of the simpler models that can simulate the non-linear and stress-level characteristics of rockfill. The most widely used is Duncan-Chang hyperbolic model.

3. BAKUN HYDROELECTRIC DAM

The Bakun Hydroelectric Power Dam will be 205 metres high with an approximate crest length of 748.85 metres and fill volume of approximately 17,000,000m³. Concrete Face Rockfill Dam features is essentially a slab of concrete placed against rockfill on the upstream slope face as “watertightness” that extends from the dam crest to the plinth. A 7.5m high “L” type concrete parapet wall at the upstream of the crest to serve as access road with a dam slope of 1V:1.4H at the upstream and 1V:1.3H at the downstream. The dam can be divided into different zones as shown in Figure 1 below (Sarawak Hidro, 2003).
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**Fig. 1**: Different zones in Bakun Dam.

**Table 1**: Different zones for Main Bakun Dam.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Designations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete slab</td>
<td>Have a variable thickness reduced with the height, based on formula 0.3+0.003H.</td>
</tr>
<tr>
<td>Zone 1A &amp; 1B</td>
<td>Both zones as supporting zones for the upstream, over the lower deck of perimeter joint.</td>
</tr>
<tr>
<td>Zone 2A</td>
<td>A well compacted of processed fine filter zone (processed fresh Greywacke). This zone also has a special cushion material with well graded.</td>
</tr>
<tr>
<td>Zone 2B</td>
<td>Has cushion material with well graded and selected from fresh greywacke, with a maximum size of 100 mm, this zone be immediately behind the face slab.</td>
</tr>
<tr>
<td>Zone 3A</td>
<td>A transition material placed adjacent to zone 2B with maximum size of 300 mm and minimum 5 mm.</td>
</tr>
<tr>
<td>Zone 3B</td>
<td>The upstream zone forming approximately 50 – 60% of the embankment including the integrated cofferdam. Consist of slightly weathered rock to fresh greywacke.</td>
</tr>
<tr>
<td>Zone 3C</td>
<td>A zone within the downstream placed and compacted in layers about 1m thick. It consists of 70% fresh greywacke with 30% mudstone. Maximum size 1200 mm to 5mm.</td>
</tr>
<tr>
<td>Zone 3D</td>
<td>This zone is placed and compacted in layers up to 2 meters thick and dozed to downstream face of the dam to serve as slope protection, also used within the valley bottom to serve a high-capacity under drain. It consist of coarse slightly weathered to fresh greywacke rockfill materials with maximum size 1500 mm.</td>
</tr>
</tbody>
</table>

4. **MODELLING OF BAKUN DAM**

Finite Element Method (FEM) is based on a theory whereby an original body is viewed as an assembly of discrete parts/building blocks. This is done using the modeling techniques and computations aspects, complex region defining a continuum is discretized into simple geometric shapes called finite element. The elements that compose the object are of finite size and hence the name of the method (FEM) The smaller the size, the smaller the errors and as a result, the solution obtained comes closer to the true solution.

A dam section problems problems involving long bodies, whose geometry and loading do not significantly in the longitudinal direction, are refereed to as the cases of plane strain. Finite
element analysis has been used to study the behaviour of rockfill and to predict strains in various portions of the rockfill. The results so far obtained are promising and the method would be used more widely in future.

Bakun CFRD dam is modeled as 2-D structure and then divided into few layers and each layer is discreted into few elements comprising of nodes depending on types of element. The geometry of the dam and the material properties in each section of the dam is designed based on actual data. Each element is discretized accordingly to respective layer and fit the type of material comprising in respective section of the dam model. For soil-structure interaction problems, in our case layer between main dam and concrete face were based that there is no slip between the structures and the soil or that there is no possibility for shear stresses to develop (interface is perfectly smooth). There are two cases of dam been considered; namely rigid foundation and flexible foundation as shown in Figure 2.

For the first case, the dam is designed on a fixed base or rigid foundation. The dam is divided into eight layers, divided into 28 layers, and then each layer discrete into 936 elements gave a total of 2870 nodes. There are 3 types of isoparametric elements used in this case; namely 8 noded isoparametric element, 6 noded isoparametric element, and interface isoparametric element. In this case, the boundary condition is fixed at the base of the dam. The latter case, the model of main dam is same as prior case and adding the foundation at the bottom of the main dam. The foundation is divided into four layers, and each layer has infinite elements on both sides. Addition to the 4 layers of foundation gave increment of 170 elements and 508 nodes gave sum of 1103 elements and 3378 nodes. The dam which divides into 32 layers is assumed to be fixed at 40m below the foundation level. Addition of infinite element gave total of 4 types of elements in this case.

![Fig. 2: Finite Element Meshes.](image)

**Left: Flexible Foundation  Right: Rigid Foundation**

The stress-strain relationship for most soil materials in nonlinear and for realistic results the analysis should take into account. In linear material properties case, the finite element analysis has no problem because properties are constant at each stress level. The non-linearity arises from the stress dependence of the stress-strain material parameters. So it was seen from literature review on CFRD dams, that the following stress-strain law has been adopted, namely, Linear elastic, Nonlinear elastic and Elasto-Plastic. Stress can be classified as shown in Table 3.

The finite element program which was written for linear analysis is modified to incorporate material non-linearity, sequential construction of the dam for non-linear analysis and incremental reservoir filling. In the case of geotechnical problems like high Bakun dam, the non-linearity arises from the stress dependence of the stress-strain material parameters. The isotropic hyperbolic model which is implemented in this study can directly capture the non-linear behaviour and pressure-dependency effects and generate the $E_i$ at each level of loading,
which includes constitutive parameters according to E-B parameters such as $K$, $n$, $R_f$, $\varphi$, $\Delta\varphi$, $K_{bs}$, $m$ are listed in Table 4 (Sarawak Hidro Sdn. Bhd.).

**Table 3: Type of stresses.**

<table>
<thead>
<tr>
<th>Type of stress</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive stress</td>
<td>By convention, engineers considers as negative.</td>
</tr>
<tr>
<td>Tensile stress</td>
<td>By convention, engineers considers as positive.</td>
</tr>
<tr>
<td>Normal stress, $\sigma_n$</td>
<td>Stress directed perpendicular to a given plane.</td>
</tr>
<tr>
<td>Shear stress, $\tau_n$</td>
<td>Stress directed parallel to a given plane.</td>
</tr>
<tr>
<td>Principal stresses</td>
<td>3 orthogonal stresses are directed perpendicular to principal planes upon no shear stress exists. $\sigma_1 \leq \sigma_2 \leq \sigma_3$ where $\sigma_1 =$ maximum compressive stress axis $\sigma_2 =$ intermediate stress axis $\sigma_3 =$ minimum compressive stress axis.</td>
</tr>
</tbody>
</table>

**Table 4: Parameters for Duncan’s E-B Model.**

<table>
<thead>
<tr>
<th>Material</th>
<th>$\gamma$</th>
<th>$K$</th>
<th>$n$</th>
<th>$\varphi$</th>
<th>$\Delta\varphi$</th>
<th>$m$</th>
<th>$R_f$</th>
<th>$K_{bs}$</th>
<th>$K_{ur}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cushion material</td>
<td>22.8</td>
<td>400</td>
<td>0.35</td>
<td>50.6</td>
<td>7</td>
<td>0.22</td>
<td>0.78</td>
<td>520</td>
<td>800</td>
</tr>
<tr>
<td>Transition material 3A</td>
<td>22.5</td>
<td>780</td>
<td>0.30</td>
<td>52.5</td>
<td>8</td>
<td>0.25</td>
<td>0.77</td>
<td>525</td>
<td>1500</td>
</tr>
<tr>
<td>Rockfill 3B</td>
<td>21.3</td>
<td>850</td>
<td>0.30</td>
<td>52.5</td>
<td>10</td>
<td>0.20</td>
<td>0.77</td>
<td>550</td>
<td>1700</td>
</tr>
<tr>
<td>Rockfill 3C</td>
<td>20.6</td>
<td>700</td>
<td>0.35</td>
<td>48.0</td>
<td>7</td>
<td>0.10</td>
<td>0.73</td>
<td>300</td>
<td>1500</td>
</tr>
<tr>
<td>Rockfill 3D</td>
<td>20.5</td>
<td>760</td>
<td>0.35</td>
<td>52.5</td>
<td>10</td>
<td>0.18</td>
<td>0.76</td>
<td>460</td>
<td>1500</td>
</tr>
<tr>
<td>Foundation</td>
<td>19.0</td>
<td>300</td>
<td>0.45</td>
<td>38.0</td>
<td>2</td>
<td>0</td>
<td>0.8</td>
<td>150</td>
<td>600</td>
</tr>
</tbody>
</table>

The Birth, Dead and Ghost element techniques which used by Norzaie has been used in Finite element program to simulate the sequence of construction of the dam and each layer is loaded with stage of construction. At reservoir filling stage analysis, At the end of Bakun dam construction, it is planned to impound water after the completion of dam body, and in the analysis the reservoir was considered to be filled in a single stage. Water loading applied normal to the upstream face. Figure 3 illustrate the sequence of loading for both cases with foundation and without foundation respectively (for first 3 stages).

**5. ANALYSIS AND RESULTS**

Non-linear analysis is very much computationally intensive than linear analysis. In linear analysis, superposition is used to calculate the results for combination load cases but in non-linear analysis, superposition is not valid. The results for a combination load case are obtained in non-linear analysis by adding together all component load cases and then performing the analysis for combined loads.
Due to the Bakun Dam is consists of 8 different section with different material properties for each section, the stresses in the upstream half of the dam could not be expected to mirror those in the downstream half and this is reflected in the contours of calculated stresses. This is contradicting of symmetrical dam that has the symmetrical zones at the upstream and downstream side, as only weight of the dam been considered; we can expect the downstream at the mirror to the downstream side.

Based on theory, the horizontal stress is greater at the lowest location of the dam, or in another word, near the base of the dam. Horizontal stress is bigger at low elevation because of the fact that in the case of a dam cross-section of less deeper height, the lateral movement of rockfill at any point is comparatively restrained on account of the proximity of rigid foundations, whereas in the case of the deeper dam cross-section, the much greater deeper of flexible rockfill material below the corresponding point allow more lateral movement of rockfill at that point, resulting in reduction of horizontal stress in the rockfill at that point. The same mechanism also applies to flexible foundation case. However, this applies to symmetrical dam. Due to unsymmetrical section of dam that have different material properties, we can observed that the maximum horizontal stress not occurs at the middle but a few meters from the upstream.

Fig. 3: Sequence of Construction of Bakun Dam.
Major principal stress shows the almost same patterns and shape with the vertical stresses. However, a major principal contour shows a bit increase in the values compared to vertical stresses (Figure 4). At the meanwhile, the minor principal stress has the same behaviour with the horizontal stress as shown in Figure 5. The major principal stress also showed almost same value compared to horizontal stresses. From the equation above, this may due to the minimal or no effect of shear stresses.

Fig. 4: Contours of Normal Stress, $\sigma_y$, at the end of construction stage with and without Foundation for non-linear analysis.

Fig. 5: Contours of Normal Stress, $\sigma_x$ at the end of construction stage for with and without Foundation for non-linear analysis.

Fig. 6: Contours of Minimum Principal Stress, $P_{\text{min}}$ at the end of construction stage with and without Foundation for non-linear analysis.

Fig. 7: Contours of Maximum Principal Stress, $P_{\text{max}}$ at the end of construction stage with and without Foundation for non-linear analysis.
In the analysis for reservoir full condition, the major and minor stresses include the stresses at the end of construction, which were fed as initial condition in the computer. In case of CFRD, the buoyancy effect is absent and the water load is applied on the upstream sloping face resulting in considerable increase in both the horizontal and vertical stresses in the upstream portion of the rockfill embankment section.

By comparison of the contours shape, the minor principal stress at the end of reservoir filling become flatter as compared to the contours at the end of construction which looks about parallel to the slope of the upstream and that due to the fact that the orientation of water pressure acting normal to concrete slab is more or less close to the minor principal stresses, $\sigma_3$ in the upstream portion of the Main Rockfill embankment at the time of completion, while the orientation of the major principal stresses, $\sigma_1$ in the rockfill are approximately perpendicular to the orientation of water pressure acting on the concrete slab. During reservoir impoundment, the increase in major principal stress is larger than the increase in minor principal stresses. This due to the decrease of deviator stresses ($\sigma_1 - \sigma_3$) means decrease in stress level and increasing in the tangent modulus, as the tangent modulus changed to the unloading tangent modulus. There is no tension stresses along dam occurred so the dam be more stable and no probability of cracking and leakage.

By comparison of major principal stresses at end of construction and end of reservoir filling which given in Figure 8 and Figure 9 respectively, the maximum value at the foundation level for end of construction of flexible foundation and rigid foundation is 3200 kN/m$^2$ and 3500 kN/m$^2$ and for end of reservoir filling is 3500 kN/m$^2$ respectively for both cases. The dam however, still considered safe as it still under allowable compressive stresses (30000 kN/m$^2$).

![Contour of Minor Principal Stress, Pmin at reservoir operations for with and without Foundation for non-linear analysis.](image1)

![Contour of Major Principal Stress, Pmax at reservoir operations for with and without Foundation for non-linear analysis.](image2)

### 6. CONCLUDING REMARKS

By using latest version of hyperbolic non-linear elastic model (Duncan-Chang, 1984), two cases of loading been considered. First case, at the end of construction under self-weights of the dam (gravity) and at the end of reservoir impoundment (the values, i.e. displacement, strains and
Principal stresses in non-linear analysis...

...stresses obtained at end of constructions are stored in the program). Like linear analysis, displacement and stresses are discussed at specified elevation in specified stages. Contour at the end of construction and end of reservoir fillings also discussed.

(i) The maximum of the normal horizontal stress $\sigma_x$ occurred at the foundation level closer to the heel of the dam for flexible foundation and about 1/3 of the height from heel at the upstream face for rigid foundation. For $\sigma_y$, due to “overburden” of the self-weight of the dam, the maximum stresses takes place at the middle of the base respectively for both cases. The major and minor principal stresses occurs at the foundation layer (at elevation 0m).

(ii) As normal stresses, $\sigma_x$ and $\sigma_y$, increases compared to the end of construction, the major and minor principal stresses increased as well. Comparison to without foundation case, with foundation has a more significance increase if looks at their contours. Like normal stresses ($\sigma_x$ and $\sigma_y$), minor principal stresses experienced increase along the upstream at the upstream slope face and major increased at middle of the dam like vertical stresses. For rigid foundation, minor principal stress has smaller value of maximum horizontal stresses but no difference between major principal stress and vertical stress.

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