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DYNAMIC ANALYSES, DESIGN DEPENDENCY AND THE SUSTAINABLE USE OF INDUSTRIAL BY-PRODUCTS FOR EMBANKMENT DAMS

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ABSTRACT

Embankment dams are widely used in areas with high risk of seismic activity because of their good performance for normal and exceptional loading cases. Linked to increasing seismicity, the dam design gets even more complex. These circumstances raise the demand for thorough knowledge of used materials and more complex and reliable numerical analysis results. This paper discusses the seismic analysis of an asphalt core embankment dam (ACED) and an asphalt faced embankment dam (AFED). Results of 2D numerical analysis with focus on the seismic behaviour are discussed. Furthermore, the use of industrial by-products as embankment fill materials is discussed. In numerical modelling various constitutive models are employed to describe the material behaviour under various loading conditions. The cyclic and highly non-linear mechanical behaviour of coarse grained materials under seismic loading makes the use of sophisticated hyperbolic material model expedient. These constitutive models can increase the accuracy of the analysis, whereas to achieve the same it requires even more detailed input parameters. Due to the heterogeneity and variety of gradation, particle shapes and mineral constituencies, the characterization of embankment materials is a challenging task. Therefore, the decision of applied constitutive models is often influenced by available material parameters, determined with field and laboratory tests, as well as through experience.

***Keywords**: Embankment Dam, Zoned Dam, Asphalt Sealing Elements, Asphalt Faced Embankment Dam (AFED), Asphalt Core Embankment Dam (ACED), Design, Numerical Model, Acceleration, Seismicity, Aggregate, Asphalt, Asphalt Concrete, Material Testing, Industrial By-Products, LD slag.*

1. INTRODUCTION

All around the globe various types of dams are used to create water reservoirs for multiple purposes. Keeping safety and finance in mind, less challenging dam locations, that concerns with aspects like foundation conditions, seismicity at dam sites, availability of construction materials etc. are preferred. Ironically, where there is a demand of a reservoir, a suitable dam location is not always available. In those cases, advanced design of dam structures become indispensable. Linked to increasing seismicity, the dam design gets even more complex. These circumstances raise the demand for thorough knowledge of used materials and implementation of more sophisticated material models in order to get more reliable numerical analyses results.

One of two case studies presented in this paper shows how numerical analyses can be used for the optimisation of a dam design. Embankment fill materials with high shear resistance are of utmost importance, especially for higher dams with steeper slopes in regions with higher seismicity (Smesnik et al. 2019).If these materials are not available in the vicinity of the site, the supplement of natural materials with industrial by-productscan be a promising solution. The same are used in various fields around the globeas a high quality construction material.Therefore, through the second case study presented in this paper, the use of LD slag, an industrial by-product of the LD steel making process, as an embankment fill material has been introduced.

2. EMBANKMENT MATERIALS AND CHARACTERISATION

For the construction of large civil structures like embankment dams, coarse grained materials (e.g., rockfill and alluvial fill) are of importance.Depending on the embankment zone and location in the dam body, the used material needs to fulfildifferent functions and requirements.There is nostrict guideline for the numbering of those zones, but the followingembankment zoning designation can be seen as a common practice:

- Zone 1 : impervious zone (can be replaced with a membrane sealing system)
- Zone 2 : the filter or transition zone
- Zone 3 and 4 : the main embankment fill (rockfill and/or alluvial fill material).

Above mentioned zones and linked functions come with different requirements depending upon grading curves and particle composition and limits. Theimpervious as well asfilter or transition materials with a maximum particle diameter of few millimetres to centimetres can be tested with standard laboratory equipment and are therefore, frequently characterised. Whereas, thematerial parameters of the main embankment fill materials (e.g. rockfill and alluvial fill) have rather seldom been tested, because of the size of the particle as it wouldrequire large-scale apparatus and affect the corresponding material testing costs.As already mentioned in the introduction, improved knowledge of rockfill material properties, particularly shear resistance for stability assessment,is of utmost importance. Constitutive models, especially models with higher ordersuch as the hyperbolic material model, require numerous determined material parameters to predict accurate material behaviour in various loading conditions. The discrepancy between available material parametersderived from material investigations and the required ones for sophisticated material models is omnipresent. (Smesnik et al. 2019)

2.1 Sustainable use ofindustrial by-products for a large civil project

Various by-products of many industrial processes are converted in secondary materials and are used globally. An example of such products is LD slag, which is one of the by-products of the LD steel making process. It is the most important steel production process worldwide and accounts for approximately two-third of the global steel production. This process is also used by the Austrian quality steel manufacturer voestalpine. Presently, the converted granular industrial by-product has been used as a construction material in many fields successfully since decades, not only in Austria but also in many other countries. In almost all countries, LD slag from a quality-controlled production is seen as a sustainable contribution to the protection of natural mineral resources with a variety of applications. When using LD slag, its high quality technical advantages are taken into account. The usage of the same is supported by the fact, that it was registered years agoas a requirement of the European REACH chemicals regulation (European Registration, Evaluation, Authorization, and Restriction of Chemicals). The registration and the result of this examination confirms that it is not a hazardous material in terms of this EU regulation and therefore, permits the use of LD slag throughout Europe. Currently, the processed material is used for instance, as an aggregate for asphalt, a raw material for the production of cement and clinkers, fertilizers, filling materials and as material mixtures for base courses without binders for road and railway construction. Corresponding standards are for example EN 12620, EN 13043, EN 13242. Voestalpine assigned AFRY to develop ways to use LD slag for various purposes in civil projects. As a result,in 2017, in spite of strict regulations and controls, a project started in central Europe with the target to use LD slag as an aggregate for concrete and asphalt as well as embankment fill material. This project comprises of a multipurpose reservoir, which is formed by two embankment dams situated in a valley. An asphalt facing was designed to seal the reservoir with a volume of 5 Mio. m^3. A comprehensive material testing program has been conducted to prove the use of LD slag as concrete aggregate for XC3 concrete (concrete in permanent contact with water) and an aggregate for asphalt in hydraulic engineering as well. Figure 1 shows produced dense asphalt with LD slag as an aggregate.

Figure 1 : Dense asphalt produced with LD slag aggregates.

A project site investigation showed a limited amount of suitable natural embankment fill materials available in the vicinity of the project site. Therefore, the use of LD slag, as an embankment fill material would reduce the amount of long distance transportation of natural fill materials, since it is available in the vicinity. As a result, voestalpine and AFRY decided to investigate in more detail the use of LD slag as embankment fill material.

A special asphalt sealing system on the dam upstream face and in the foundation in combination with a downstream mineral sealing have been designed to avoid the contact of the LD slag embankment with water. Possible seepage is collected with a drainage system located in the dam foundation and guided to a water treatment system. This measure furthermore ensures the safe use of LD slag as an embankment fill material in the mentioned project.

For the judgment of the suitability of LD slag as embankment fill material, in-situ and laboratory tests have been carried out, prior and during the initial project phase to determine strength, stiffness and hydraulic material parameters. An exemplary grading curve of the fill material is given in Figure 2.

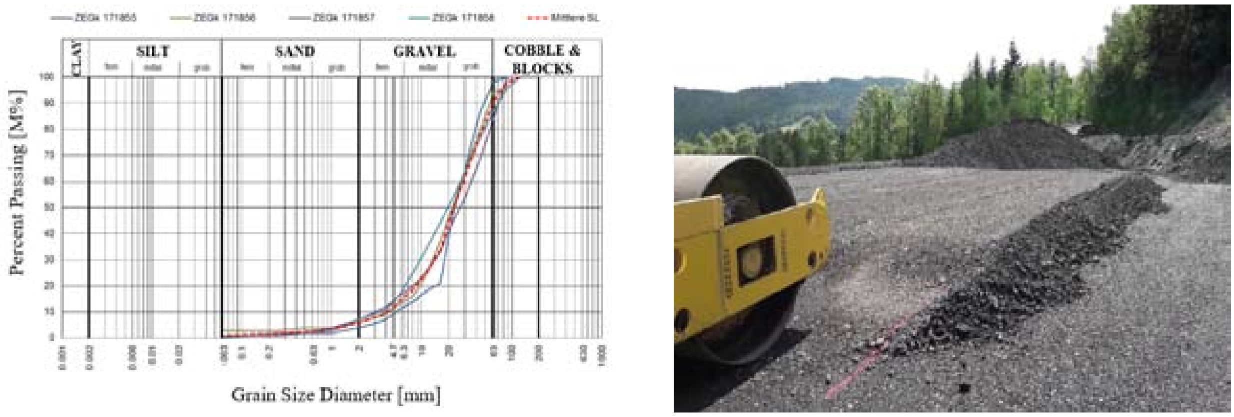

Figure 2 : (left.) LD slag grading curve; (right.) large-scale trial embankment.

Large scale in-situ trial embankments(Figure 2, right) confirmed the experiences of goodcompactibility gained from the landfilling process. The test results showed further high mechanical hardness, high strength due to 100% angularity of the aggregates and a high resistance against abrasion.Average LD slag material parameters derived from material testing results,in comparison to the available rockfill material(quarries in the vicinity)are given in Table 1.

Table 1 : Determined average material parameters of LD slag and rockfill material

Material parameters	γ [kN/m³]	φ' [°]	c' [kN/m]	ψ [-]	νur[-]	kf[m/s]
LD slag	24.5	39	0	0	0.2	10-3
Rockfill	23	43	0	13	0.3	10-3

Stress dependent stiffnesses of the LD slag as well as for the rockfill material (average rockfill quality available in the project region) shown in Figure 3,have been calculated according to theOede Formel.Based on the test results and derived stress dependent stiffness shown inFigure 3**Error! Reference source not found.**, the LD slag has been considered as a suitable dam fill material for dam zone 3, in addition tothe common acceptance as a concrete and an asphalt aggregate.

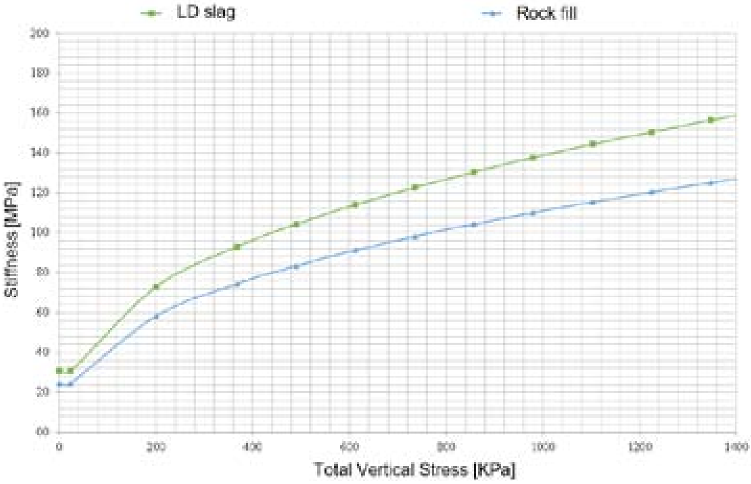

Figure 3 : Stress dependent stiffness of LD slag versus rockfill material

3. NUMERICAL ANALYSIS AND DESIGNDEPENDENCY OF EMBANKMENT DAMS WITH ASPHALT SEALING ELEMENTS

The first step in dam design shallalways be the creation of a reliable geological model and the assignment of material parameters.In the second step, theactual dam design process can begin. In this stagenumerical analysis area powerful tool amongst others. The same canprovide a detailed and accurate information about the stress/strain and deformation behaviour of the dam structure in various loading conditions.But, it shall be kept in mind, thatresults of numerical analysis are directly dependent upon the quality of the input parameters and modelling. Furthermore, the effort for the same increases drastically with the level of modelling detail. Therefore, desired information and results gained by the analysis should be determined in advance to avoid needless efforts.

Nowadays, dams are built in regions with less favourable conditions, which requires more sophisticated dam design. The demand of more cost and resource efficient designs is another concern.More advanced dam design and increased demand of result accuracy comes oftenalong with the use of high order constitutive models. The same in turn requires, as mentionedearlier,a lot of material testing to determine requiredinputparameters for the constitutive model. Keeping the dam zoning and resulting various construction materials into account, the proper use of high order material models can cause a certain effort of material testing.

Besides the embankment material and related behaviour,the sealing system has a crucial influence on the dam safety. Clay core embankment dams (CCED)are undisputedlyone of the most suitable dam types for regions with higher seismicity. Considering the fact that CCED requires a sufficient amount of clay and unavailability of the same makes it imperative to have another suitable dam type for seismic regions. Dams with asphalt sealing systems, like asphalt core embankment dams (ACED) and asphalt faced embankment dams (AFED) can bean alternative. However, the former has several advantages due to the location of the sealing system within the dam. (Feizi-Khankandi et al. 2009)These two types have as shown in Figure 4 a thin but very flexible membrane sealing element.In addition to the flexible sealing element, a proper filter design is mandatory to further increase the suitability for seismic regions. ACED and AFEDpossessa fast construction process with a flexible sealing system. Another advantageis that the asphalt sealing system and the material characteristics of the asphalt can be tailor suited in terms of flexibility according to site conditions. (ICOLD 2018)

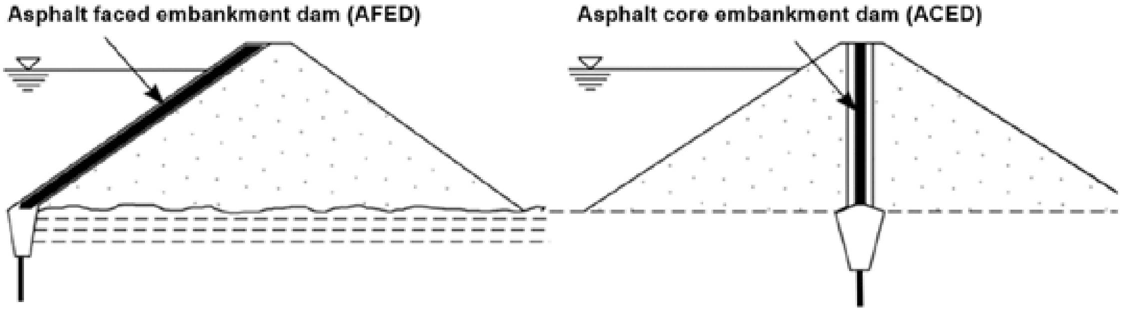

Figure 4 : (left.) Asphalt Faced Embankment Dam - AFED (right.) Asphalt Core Embankment Dam -ACED.(Smesnik et al. 2017)

In the following sections,two case studies are presented in order to showcase, how numerical modelling can be used in the dam design process to solve various design issues. These studies are focusingprimarilyon the seismic behaviourof two embankment dams with asphalt sealing elements and the design dependency.

Case study one,shows in brief how the suitability of an industrial by-product, as main embankment fill material for an AFED has been investigated. Case study two, shows the optimisation of the dam zoning of an ACED, in order to increase the dam safety and to reduce the construction costs respectively. It needs to be stated, shown studies are only a small extract of the entire design process.

3.1 Numerical analysis and design considerations

As a result of the valley shape and the predefined dam geometry, 2D numerical analysis have been judged for both cases as sufficient. In spite of the fact, that the AFED and ACED are located in central Europe andAsia respectively, both have considerable high peak ground accelerations (PGA) subjected to the region (SEE_{AFED} = 0.22 g; SEE_{ACED} = 0.65 g). Both case studies are in different design stages. Therefore, the numerical modelling approach slightly differs, accordingly.

For the 2D numerical analyses,the software GeoStudio 2018 has been employed. In order to obtain the desired analysis, various software packagesin combination with numerous type ofanalyseshave been combined within GeoStudio. Following software packages have been used for the performed analysis:

1. SEEP/W for seepage modelling
2. SIGMA/W for stress-deformation modelling
3. SLOPE/W for stability modelling
4. QUAKE/W for dynamic modelling.

An advantage of the employed software is the possibility of performing coupled analysis with different software packages with manageable efforts. In this way, for example the calculated pore water pressures, stresses and deformations can be taken from the parent analysis, if judged as sufficient.

3.2 Case study one – industrial by-product as embankment fill material for an AFED

The discussed AFED, with a height of 80 m is part of the,in section 2.1mentionedproject in central Europe.In the sameLD slag, an industrial by-product of the steel making process,is considered to be used as high quality embankment material. As already indicated by material tests and derived material characteristics, the suitability of LD slagas embankment fill material have been further investigated with numerical analysis of the dam structure. For the current basic design, mainly the linear elastic and equivalent linear material model have been employed for static and dynamic analyses, respectively.The following analysis approach has been used:

1. Steady-state seepage analysis (SEEP/W)

2. Initial Static/ Load Deformation analysis (SIGMA/W)
3. Equivalent linear dynamic analysis (QUAKE/W)
4. Newmark deformation analysis (SLOPE/W).

As already mentioned LD slag is globally used for various purposes, but as an embankment fill material for a large civil structure like an embankment dam is unique. Static material parameters have been tested with laboratory and in-situ tests. Gained material parameters have been compared with literature and test results from previous executed projects (road construction, landfills etc.). Determined static material parameters are shown in Table 1 and Figure 3.To perform mentioned dynamic numerical analyses, the determination of dynamic materials parameters was indispensable. Testing of dynamic material behaviour of coarse grained materials requires more effort and is a challenging task.Therefore, when these test results are not available it is a common practice to select the required parameters according to literature. The same approach has been chosen for the basic design stage of the discussed project. This approach was possible due to the similarities between the material characteristics and behaviour of LD slag and rockfill. According to similar material behaviour between LD slag and rockfill under static conditions, as shown in Table 1, dynamic material parameters presented inFigure 5 and Figure 6have been determinedon the basis of literature.(Seed et al. 1984)

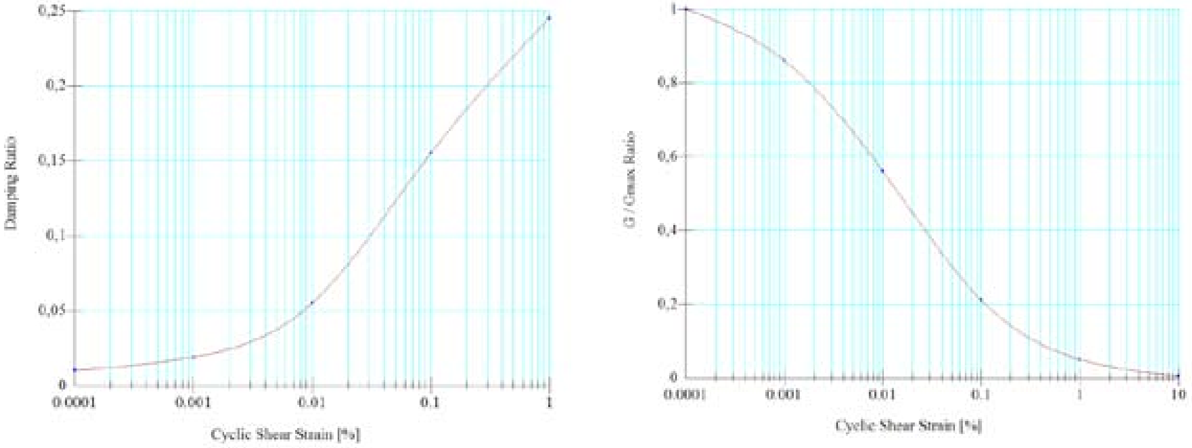

Figure 5 : (left.) Damping ratio function used in the dynamic analyses for LD slag material; right.) G-reduction function used in the dynamic analyses for LD slag material.

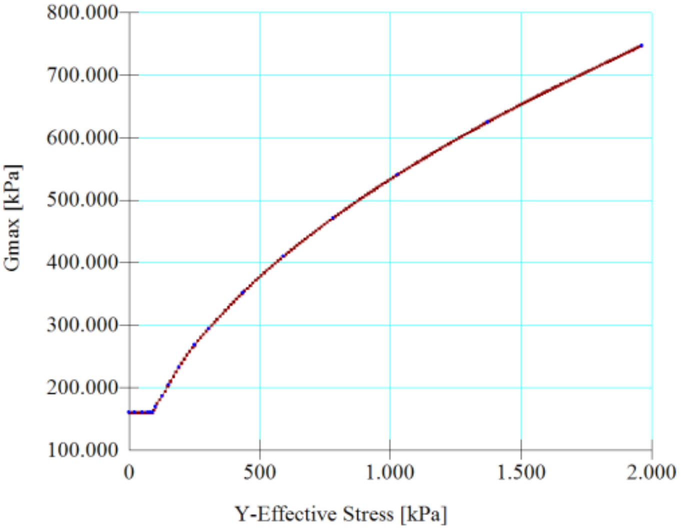

Figure 6 : G_{max} function used in the dynamic analyses for LD slag material.

The results of performed static as well as dynamic numerical analyses showed expected deformation patterns of an AFED. Therefore, it indicates that the use of LD slag (with determined material parameters) as ahigh quality embankment fill material is suitable for embankment dams. Another advantage of the similarity between rockfill and LD slag is that both materials can be easily combined within the embankment.

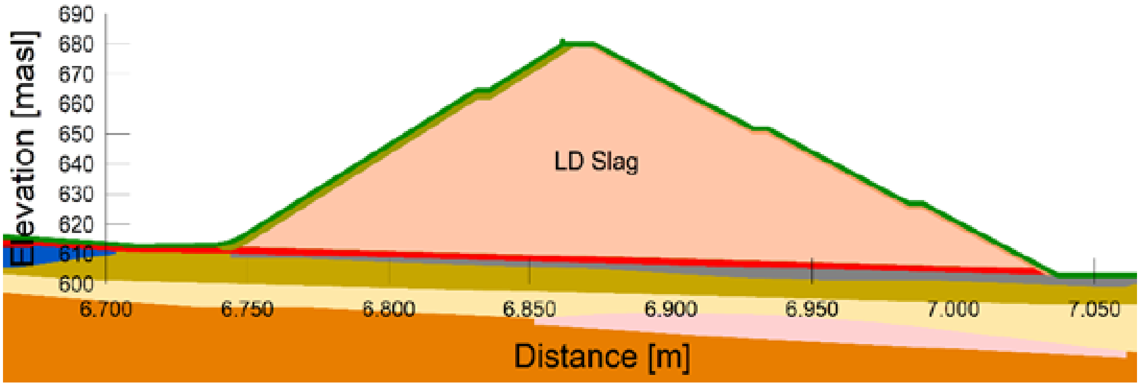

Figure 7 : AFED – main cross section

This case study showed how industrial by-products like LD slag can be used as a high quality embankment fill material and therefore, be used in a sustainable way.

3.3 Case study two – optimisation of dam zoning of an ACED

The discussed 95 mhigh ACED is located in a high seismic region in Asia. Therefore, it is necessary that the dam can withstand high deflections and deformations due to earthquake shaking without losing the overall structural integrity. Another aim in the project was the reduction of the rockfill quantity and linked construction costs by using on site available alluvial fill material from the river dredging process. Considering these requirements, the dam zoning has been optimised based on comprehensive numerical analysis.The following analysis approach has been used:

1. Steady-state seepage analysis (SEEP/W)
2. Slope stability analysis (SLOPE/W)
3. Load-deformation analysis (SIGMA/W)
4. Equivalent linear dynamic analysis (QUAKE/W)
5. Newmark deformation analysis (SLOPE/W)
6. Dynamic deformation analysis (SIGMA/W).

The basic design considerations of the dam zoning presented in Figure 9, are linked to the material characteristics of the two main fill materials (rockfill in brown and alluvial fill in green shades). On one hand the rockfill portion stabilises the dam slopes due to high shear strength and on the other hand the alluvial fill zone with comparable high stiffness provides proper support for the filter zones and the asphalt core. Firstly, an outline of the dam zoning has been determined with pseudo-static slope stability analysis. By taking high peak ground acceleration (PGA) values into account, dynamic analysis become mandatory.In the next step, the suitability of the initial dam zoning derived from pseudo-static results has been investigated in exceptional load cases through various dynamic analyses.To avoid excess pore water pressure, in the event of earthquake shaking, horizontal drainage layers in the upstream dam shoulder are implemented.Due to the dam zoning, drainage layers and available material characteristics, linear elastic and equivalent linear material model have been employed for analysis. As the modelling approach described above, inter alia Newmark deformation analysis have been considered to determine the thickness and the shape ofrequired upand downstream rockfill zoning. An example of a sliding block configurations can be seen in Figure 8.

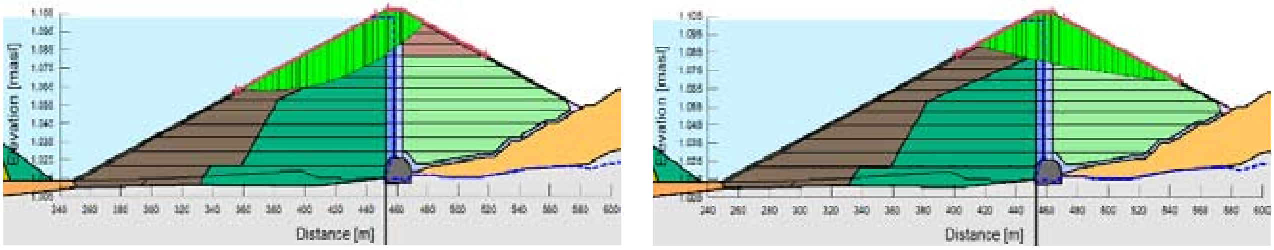

Figure 8 : Exemplary sliding block configuration of Newmark analysis

The optimised dam zoning shown in Figure 9is a result of an iterative process, which required numerous analyses steps. The final results of the static and dynamic analysis, performed with the optimized dam zoning, showed expected deformation patterns of an ACED (e.g. (Feizi-Khankandi et al.2009),(Hoeg 1993), (Committee on seismic aspects of dam design 2009). The suitability of the zoning in normal and exceptional load cases has been confirmed by final analysis.

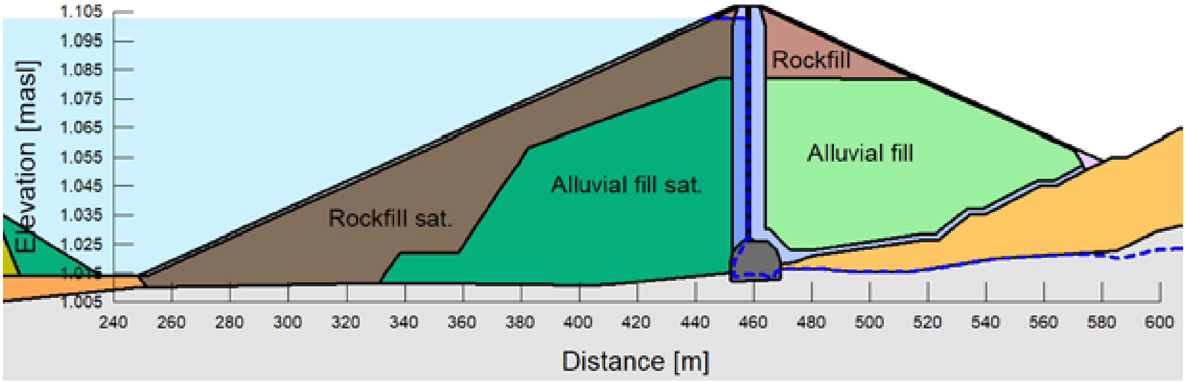

Figure 9 : ACED - optimized dam zoning.

With the introduced modelling and design approach, a reduction of the required rockfill quantity of approximately 50 % of the total fill volume has been achieved. In addition to cost effectiveness there is also a positive effect on the environment due to reduced blasting and transportation in the quarries.

4. CONCLUSION

Embankment dams are widely used in areas with high risk of seismic activity because of their good performance in normal and exceptional loading cases. Not only the dam type, but also the local conditions, available materials etc. have a crucial impact on the performance of the structure while in service.For advanced dam designs,comprehensive numerical analysis are of utmost importance. It is not only the use of advanced modelling techniques and the application of sophisticated material models which leads to a satisfying dam design, but also the smart use and combination of the same. In other words, the use of constitutive models shall be judgedbased on availablematerial parameters and the desiredresults and information.Numerical modelling enables the designer to study the dam behaviour under various loading conditions. Different dam zonings and the influences on the stress/strain development within the dam body can be analysed with acceptable efforts. Through gained results and information, the designer can create tailor suited dam designsto fulfil the design requirements.The case studies presented within this paper, confirmed the common agreed suitability of embankment dams for seismic regions.

The first case study presented in this paper, talks about how to bring sustainability and make embankment dams more cost effective by the use of industrial by-products as embankment fill materials.For the construction of a 80 m high asphalt faced embankment dam,the use of LD slag as embankment materials has been studied. LD slag is a by-product of the LD steelmaking process.This process is the most important steel production process worldwide and accounts for approximately two-third of the global steel production.Results of in-situ and laboratory testing showed that the LD slag can be used as embankment fill material and has comparable material characteristics tohigh quality natural materials. Furthermore, similarities in the material behaviour between rockfill and LD slag have been shown. The results of carried out numerical analysis confirmed the suitability of LD slag as an embankment fill material.Large scale infrastructure projects, like embankment dams for various purposes requires an economical and efficient use of resources. Therefore, the use of industrial by-products in combination with tailor suited dam designs can be a valuable contribution to a more sustainable use of resources and better environment.

The second case study showed how numerical analysis can support a cost efficient design, through the optimisation of the dam zoning of a 95 m high asphalt core embankment dam, situated in a high seismic region. The zoning has been optimised in a way that on site available materials with comparable low shear strength could have been partly used. The zones which required high strength processed rockfill have been minimised in order to have a more cost effective design.

REFERENCES

Committee on seismic aspects of dam design (ICOLD). *Selecting Seismic Parameters for Large Dams*. 2009.

Feizi-Khankandi, Slamak, et al. “Seismic Analysis of the Garmrood Embankment Dam with Asphaltic Concrete Core.” *Soils and Foundations*, vol. 49, no. 2, 2009, pp. 153–66, doi:10.3208/sandf.49.153.

Hoeg, K. *Asphaltic Concrete Cores for Embankment Dams*. StikkaTrykk, 1993.

ICOLD. *Asphalt Concrete Cores for Embankment Dams (DARFT)*. 2018.

Seed, B., et al. *Moduli and Damping Factors for Dynamic Analyses of Cohesionless Soils*. 1984.

Smesnik, M., et al. “Laboratory Method to Simulate Short-Term Aging of Hot Mix Asphalt in Hydraulic Engineering.” *Construction and Building Materials*, vol. 150, 2017, doi:10.1016/j.conbuildmat.2017.05.207.

Smesnik, M., et al. *Determination of Rockfill Shear Parameters for Dam Stability Analysis of an Embankment Dam*. 2019, pp. 1–8., ECSMGE