Displacement analysis of dam based on material parameters using numerical simulation and monitoring instrumentation

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Displacement analysis of dam based on material parameters using numerical simulation and monitoring instrumentation

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1 Introduction

Utilization of water as basic natural resource can be done by constructing dam structure. One factor to be considered in analysis embankment dam is material parameter. During operational condition, material parameter value can be uncertain and different from its design due to weather and construction method in the past. In addition, instrumentation data is not usually available during initial design stages, therefore laboratory data will likely be the initial or only method used to estimate material properties for predicting deformation (displacement/ settlement and horizontal deformation). On the other way, it is normally very difficult to take up soil samples for testing again the material parameter, especially from the central impervious part, since this might affect the dam performance and the safety of the dam.

Thus, it is needed recently analysis for material parameter that can be used for analysing the dam in operational condition and can have accordance with its condition in field using non-destructive method. The method can be performed by numerical modelling simulation.

Furthermore, safety of earth dams depends on the proper design, construction, and monitoring of actual behaviour during the construction and during operation of the structure [1]. In the dam, besides seepage and slope stability, deformation is one factor that must be noticed. The major effects of deformations are loss of freeboard, damage to appurtenant structures located within or upon the dam, loss of confidence in the dam due to swayback appearance, cracking of the embankment (most detrimental to the impervious core), development of localized zones susceptible to hydraulic fracturing, and failure of instrumentation [2].

By monitoring deformation in the dam using instrumentation can provide early warning system in case of abnormal behaviour of the dam. It also can be used as a tool for verification the design parameters where geotechnical parameters are of the highest importance. Thus, one of displacement calculation function is also for estimating design of camber in dam crest, so that can accommodate settlement not only at consolidation but also pre-consolidate moment. This is because excessive crest settlement can cause overtopping in the dam.

Magnitudes and directions of embankment deformations are controlled by foundation and embankment material properties, abutment and embankment geometry, type of construction equipment used and embankment placement rates, reservoir loading conditions, and stress distribution within the various zones or layers within the embankment and its foundation [2]. Material properties associated with displacement are Young's modulus and Poisson's ratio.

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Due to these reasons above, therefore in this research discuss about displacement of dam. Before analysing the displacement, its need to analyse the material parameter in case value of Young's modulus and Poisson, thus can be appropriated with condition in the field. Back analysis method is used to evaluate result of modelling and result of instrumentation monitoring in dam by settlement gauge. Thus, when the Young's modulus and Poisson have been obtained, the displacement analysis dam using numerical simulation can be done. This study located on Sermo Dam which is embankment dam and located in Yogyakarta, Indonesia. Variations of stresses may occur at different elevations and in different zone of a dam [1]. Thereby in this study the review is on the core zone at different elevations so that result of this study attempts for displacement distribution in the core zone of dam's body.

2 Case Study of Embankment Dam

This study took study case in Sermo Dam which is a zonal rock fill-embankment dam type with impermeable layer in core is clay. Sermo Dam's layout can be seen in Fig. 1 which the cross sections consist of Sta 12, Sta 15, and Sta 18. In this study, the review was on the Sta 15 due to it is availability of Settlement Gauge as instrumentation to monitor displacement of dam's body.
Materials forming in each zone on Sta 15 of Sermo Dam can be seen in Fig. 1 [3]. Moreover, Sta 15 formed by material explained in following below [3] :

- Core zone : clay fill
- Filter zone : medium sand finer gravel
- Transition zone : volcanic breccia rock with maximum grain diameter of 60 cm
- Shell zone : volcanic breccia rock with maximum grain diameter of 100 cm
- Rip-rap zone : volcanic breccia rock with maximum weight each grain is 450 kg
- Bedrock zone : breccia andesite rock with some intercalation of andesitic lava

Fig. 1 shows that there are two settlement gauges placed on Sta 15, Settlement Gauge-1 located in the core and Settlement Gauge-2 located in the shell zone. In each of settlement gauge comprises of measurement rings to know the settlement occurred in each layer.
Settlement Gauge-1 has thirteen rings meanwhile Settlement Gauge-2 has nine rings.

For any large or hazardous dam, the designer should assume some cracking of the core is inevitable [2]. In the core zone is a zone that has greatest potential of displacement in the dam. Preventive analysis about displacement is needed to overcome what will happen in the future when dam in operational condition. Thus, the review of this study is in the core zone. Thereby, using Settlement Gauge-1 as the evaluating result. As research by Pytharouli and Stiros [4] which analysed vertical displacements of all seven control points located at the crest of the Kremasta dam. The result showed that maximum displacement was observed at a control point located at the middle of the crest which is impermeable clay core zone.

Furthermore, analysis in this study was conducted by numerical modelling simulation using PLAXIS 2D approach. Geometry model of Sermo Dam on Sta 15 was depicted through PLAXIS modelling, same as with geometry model in real condition (Fig. 1). However, simplification was needed for modelling the bedrock geometry in PLAXIS due to the shape of bedrock itself. The geometry shape on the bedrock based on the actual condition is irregular. This means that the bedrock layer is not straight form from upstream until downstream of the dam. Therefore, simplification in this case study is by making the bedrock layer geometry simpler. Furthermore, as restriction, for the parameter material value of rip-rap zone was equated with the parameter material in shell zone. In addition, very fine type of meshing was used in this modelling. The failure behaviour criteria is a function of the cohesion and friction angle parameters.

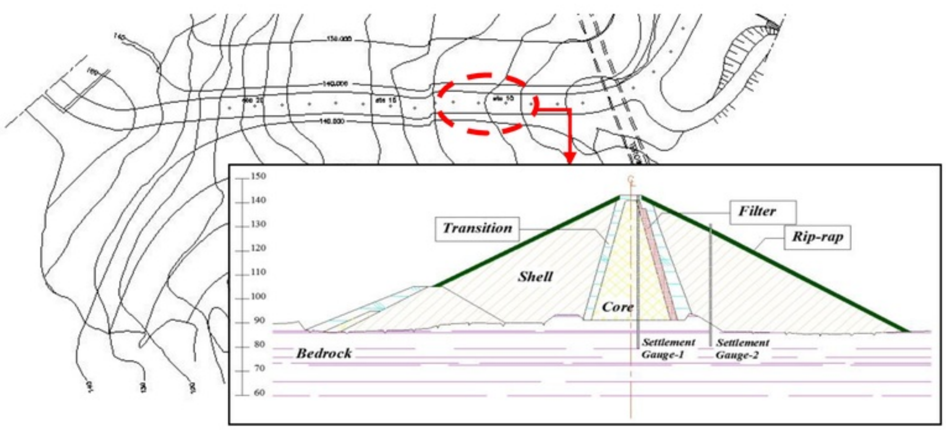

Fig. 1. Sermo Dam's Layout; Inset: Cross Section Sta 15 and Location of settlement gauge [3]

3 Research method

Material parameters for Sta 15 of Sermo Dam can be seen in Table 1 [5]. This value of the material parameters in Table 1 has been adjusted so that it is not equal to the value of the material parameters at the time of its initial design.

Table 1. Parameter Material of Sta 15 Sermo Dam [5]

Material Parameter	Zone of Dam				
	Core	Filter	Transition	Shell	Bedrock
$\gamma_{saturated}$ (kN/m^3)	18.74	21	21.7	21	21.82
$\gamma_{unsaturated}$ (kN/m^3)	15.41	18.5	21.6	20	20.12
Cohesion (kN/m^2)	8.3	0.001	0.001	0.001	680
Friction Angle	32	35	35	43	55
Permeabil -ity coeff. (m/day)	2.32 x 10^{-4}	134.1	14.292	12154.69	6.0

In this model, interface among soils are not applied. This is due to as restriction, interface is applied only between soil and structure, such as pile (concrete) and soil. Furthermore, selection of Young's modulus and Poisson's ratio became focus on this research because of the correlation with displacement that would be discussed in more detail. The analysis was done by approaching based on literature due to the limitation of data's field. However, validation using instrumentation of Settlement Gauge still used.

According to design data, core and filter zone are composed of clay and gravely sand, thus Young's modulus value and Poisson could refer to literature [6], which appropriate with the requirements for these materials. Shell zone is composed of breccia sedimentary rock. Based on Department of Public Works data design [7], shell zone has heavy volume 21 kN/m^3, cohesion 0 and friction angle 43^0. Under these conditions, thus the breccia rock approaches with sandstone material properties (adapted from Bowles and Das [6,8], and sandstone is same as with breccia rock which is a sedimentary rock. Therefore, value of Young's modulus and Poisson shell zone are used in accordance with the range of values for the material properties of sandstone, but less than material properties of bedrock. In the transition zone is also composed with breccia rock. This zone is a transition from filter and shell, with the material properties are based on sandstone. Briefly, value of Young's modulus and Poisson each zone of dam model can be seen in Table 2.

These values of Young's modulus and Poisson would influence displacement result of PLAXIS modelling. Thus, for next step, as explained above, using back analysis method to determine the value of material parameters. Values of Young's modulus and Poisson would be selected under condition that the displacement result of model has resemblance with displacement result from instrumentation of Settlement Gauge.

Table 2. Parameter Material (Young's modulus and Poisson's Ratio) for PLAXIS Modelling

Zone of Dam	Parameter	
	Young Modulus (E) (kN/m^2)	Poisson (v)
Core	5000	0.45
Filter	120000	0.35
Transition	150000	0.35
Shell	200000	0.40
Bedrock	210000	0.45

In other words, displacement result from PLAXIS analysis was compared with displacement from Settlement Gauge monitoring in the field. This back analysis method review was taken in core zone that prone-zone area and also considers of type of materials used. The smallest deviation will be selected for the next step for analysing displacement happened in the dam model. Instrumentation monitoring used is Settlement gauge on March 17th, 1997 with water level 135.20 meters [9]. In this condition, displacement had been stable which was monitored with Settlement gauge, 0.807 meters with average of displacement was 0.528 meters [9]. After that, displacement analysis from model simulation can be conducted. The location of displacement review in this model simulation refers to location of Settlement gauge-1 in the field (Fig. 1).

According to Pytharouli (2007) in Pytharouli and Stiros [4] which had a case study in Kremasta dam, one of possible mechanisms affecting crest settlement is reservoir level fluctuations. Because of this reason, in this study used several data of water level too which consists of minimum and maximum water level. Selection of these water levels based on real condition measurement using Peil Schaal in the field and availability of Settlement Gauge's data. This is due to measure of Settlement Gauge in the field is done every seven days. According to [9], it was obtained water level and Settlement Gauge's data records from 1996–2015. From these data, it could be determined the minimum water level happened was 116.79 meters and the maximum water level was 136.87 meters. In addition, for normal water level occurred in 136.60 meters. It was not only in design record but also actually happened in field. Due to small difference height between maximum water level and normal water level, thus in this study was not analysing the normal water level. Thereby, in this study analysed displacement in minimum and maximum water level happened in field.

4 Results and Discussion

As explained in the research method that analysis of Young's modulus and Poisson's ratio in this study were conducted by back analysis method. Simulation

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modelling using PLAXIS was starting from before construction (there was bedrock only), after construction (dam had been built), and when there was water level condition. The parameter materials, heavy volume, cohesion, and friction angle, used value in Table 1 that had previously been analysed. Meanwhile, for Young's modulus and Poisson's ratio based on Table 2.

By using parameters in Table 2, in PLAXIS modelling, showed that dam structure collapsed at the end of construction stage. This could be happened likely due to an imbalance between load and displacement which was happened. The reason is the large difference Young's modulus in the core, filter, and transition. Huge difference value of modulus has great potential in arch phenomena that can make hydraulic fracturing happened [10]. It can be one assumption why this model was collapsed. Zone between shell and core zone (filter and transition) can be bridge for decreasing arch phenomena in the dam [10]. This is because embankment zoning is important to minimize differential settlements, thereby reducing the potential for cracking of the core or development of zones susceptible to hydraulic fracturing [2] that could lead to internal erosion.

Thereby, this failure of model indirectly showed that selection of Young's modulus's value in modelling (based on Table 2) was not suitable with dam condition in field. Thus, Young's modulus for filter zone and transition was changed, but still in the range of Young modulus in sand material based on Bowles [6]. On the other hand, Young's modulus core zone was considered in accordance with Young's modulus in soft clay [6]. Alteration of Young's modulus and Poisson's ratio were used for finding the best value of displacement which has accordance with displacement in the field. Changing of parameter Young's modulus and Poisson's ratio can be seen in Table 3.

The value of Young's modulus and Poisson's ratio as shown in Table 3 had maximum displacement 0.554 meters in core which had difference 4.92% when compared with the result of monitoring settlement gauge, 0.528 meters. Then, Young's modulus for core zone was changed again by trial error method, so that it makes over the stiffness of core zone becomes more similar with Settlement Gauge's result in the core.

Table 3. Value of Parameter Material for Finding Resemblance Displacement Value between Numerical Simulation and Settlement Gauge

Zone of Dam	Parameter	
	Young's modulus (E) (kN/m^2)	Poisson (v)
Core	5000	0.45
Filter	6000	0.30
Transition	8000	0.30
Shell	200000	0.35
Bedrock	210000	0.45

As the limitation, value of Poisson's ratio in this study would not be changed, so that the alteration value of displacement was based on Young's modulus. Variation of Young's modulus core was done from 6000 kN/m^2 to 4000 kN/m^2, which was given range every 500 kN/m^2.

The result showed that an increase in water level causes increased in displacement result. Furthermore, the value of displacement using modelling was 0.530 meters by Young's modulus 5500 kN/m^2. This displacement almost equal with the displacement based on monitoring Settlement Gauge-1 in the field, 0.528 meters. It means that deviation was 0.38%. Thus, for the next step for analysing displacement in core zone was using 5500 kN/m^2 as the value of Young's modulus core.

Displacement analysis in this study was in the core zone of Sta 15 Sermo Dam. Result of displacement from numerical simulation (modelling) and settlement gauge (instrumentation) can be seen in Fig. 3 for minimum water level (116.79 meters); and Fig. 4 for maximum water level (136.87 meters). Both of Fig. 3 and Fig. 4 show the distribution of displacement in the core zone based on the differences of water level. In these Fig.s, Y-coordinate is elevation of dam, whereas the X-coordinate is displacement's value of dam.

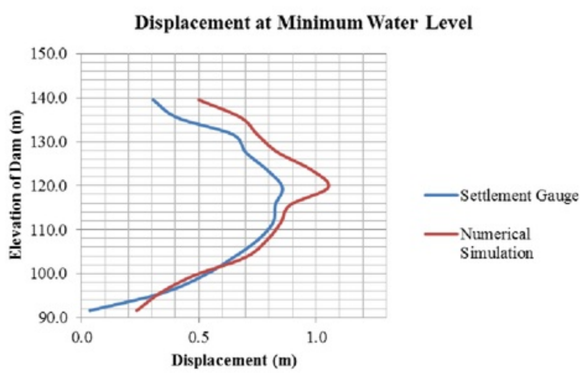

Fig. 3. Displacement Result Between Modelling Simulation and Monitoring Instrumentation (Settlement Gauge) at Minimum Water Level (116.79 meters)

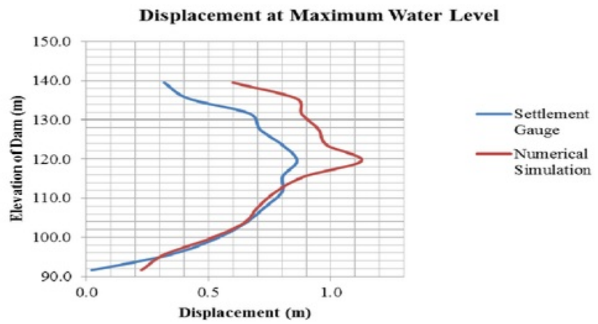

Fig. 4. Displacement Result Between Modelling Simulation and Monitoring Instrumentation (Settlement Gauge) at Maximum Water Level (136.87 meters)

Furthermore Fig. 3 and Fig. 4 show that result from numerical simulation is greater than instrumentation monitoring. Modelling of a dam might not be completely matched with the reality and instrumentation data [11]. This is due to unavoidable feature of embankment dam engineering, such as soil properties that may be affected by the weather or by the contractor's method of construction. As the result during first filling, the amount of the collapse settlement in rockfills depends on the quality of the material and the extent of its compaction [12]. With an increasing usage of poor grade rockfills, a significant settlement is becoming more common, which could lead to instability in the body of the dam and damage to rigid structures on the dam crest.

Thus, although it had been validating between material parameter and instrumentation monitoring, the result data still not same as exactly with result in the field. However, these numerical simulation results have trend which is in line with instrumentation monitoring. This numerical simulation indicates quite similar displacement behaviour with instrumentation result. The result shows that maximum displacement happened in the middle of core zone dam. This result has agreement with Chrzanowski and Massiéra's research in Diamond Valley Lake Project which is embankment dam [1].

Valley Lake Project consists of three dams which formed by soil and rock. The observation of their research was West Dam with height of 88 meters. They acquired that the maximum settlement in the center of West Dam is 0.23 meters. This is located at the 54 meters elevation [1].

From the analysis result, by knowing material parameter is required due to its influence in simulation modelling result. Determining the parameter material in analysis modelling should be validated with field data to obtain accurate model results.

5 Conclusion

Displacement analysis is important because it can show stability and potential damage of dam. Geotechnical parameters of dam material play significant role to identify prediction of displacement during operational condition. By comparing results of displacement between simulation numerical model and monitoring instrumentation method can verify the design parameters of the investigated dam. The simulation numerical results in this study present a good agreement trend with the monitoring instrumentation results. Moreover, the simulation numerical result is greater than monitoring instrumentation result.

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PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6