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Application of Finite Element on Seepage Analysis of Embankment Dams

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Abstract— *Embankment dams have better stability than homogeneous earth dams, resulting in a slimmer design in volume. The weakness of embankment dams lies in the core zone which functions as an impermeable zone. Embankment dams with zonal core is a combination of various material properties. Geometric design and drainage will affect seepage and phreatic line properties that occur, which is due to the complexity of geometry, material parameters and boundary conditions. Thus, the calculation is not as simple as in a homogeneous soil fill dam. The Finite Element Method (FEM) numerical modeling has been widely used for the analysis of seepage and dam stability. The combination of permeability coefficient parameters (k), reservoir water level (h) and seepage path length (L) based on Darcy's and Casagrande's Laws can be used to determine the relationship between seepage parameters in the core zone. This two-dimensional (2D) modeling considers saturated/unsaturated conditions and steady state conditions for each parameter.*

Keywords— *Dam, Embankment, Finite element, Seepage Analysis.*

I. Introduction

In general, dams in Indonesia are embankment type. Embankment dams have better stability than homogeneous earth dams [1], thus enabling a leaner physical design in volume. However, the weakness of the embankment dam lies in the core zone which functions as an impermeable zone. Embankment dam with zonal core is a combination of various material properties. Geometric design and drainage will affect seepage and phreatic line properties that occur [2, 3] due to the complexity of geometry, material parameters and boundary conditions. Thus, the calculation is not as simple as in a homogeneous soil fill dam. Reservoir inundation is a critical stage in an embankment type dam. At this stage, the embankment material will change due to the influence of additional water loads in the reservoir [4].

A rock-fill type dam that has an impermeable core in the form of a layer of clay standing upright in the middle of the dam body. The dam was built through a process of stockpiling a number of materials in the form of gravel, rock, sand and soil which were formed with a certain slope and height so that they could inhibit or raise the water level in the upstream [5, 7]. Dams with the type of embankment are very susceptible to collapse due to hydrostatic water pressure, pore water pressure and earthquake loads received as well as from the geometry of the dam itself. Therefore, slope stability and water seepage discharge in the dam body need to be analyzed so that the dam construction is safe from potential landslides [8].

The weir structure must be analyzed in such a way as to produce an optimal design to withstand the loads acting on the structural elements [4, 9, 10]. Calculation of these loads will be calculated using a numerical method, namely the finite element method. In principle, the finite element method divides a continuum into smaller parts called elements, so that the solution in each small part can be solved more simply [2, 11, 12]. The results of the analysis will show the possibility of landslides or erosion in parts / areas of the dam body, either upstream or downstream [13]. Thus, it is necessary to analyze seepage and stability with pre-construction loading conditions, minimum water level, and maximum water level analysis. The problem of the destruction of the weir structure can be caused because the structure is not strong enough to withstand horizontal and vertical loads around it [1].

The problem that will be discussed in this study is the formulation of the finite element method of the differential equation for seepage flow in the dam body, which occurs with the contribution of the free water surface factor. This differential equation is derived from Darcy's law which applies to the flow of seepage potential. The formulation will then be made into a computer program to analyze the water level (water potential) that seeps into the body of the dam, with the geometric form of linear elements (2 dimensions) or geometric boundaries of elements in the form of straight lines. According to Simatupang [8], numerical modeling Finite Element Method (FEM) has been widely used for the analysis of seepage and stability of a dam.

II. Method

The method used in this study is a descriptive method, namely direct observation at the research site and recording things that need to be done as well as conducting laboratory tests on the materials used in the dam body. The materials used in this study include stone, krakal, gravel, sand, and soil, in certain positions with a function as a buffer or lifting the surface of the water contained in the reservoir. The physical model of the embankment type dam is made with a model ratio of 1: 1000. The physical model is made in the hydraulics laboratory, for further analysis of seepage on the dam model. Analysis of soil physical properties was carried out using soil test, direct shear test, sieve analysis and hydrometer methods. Furthermore, the Atterberg limit test includes the liquid limit and the plastic limit. Plasticity index, specific gravity test, falling head test and constant head test were also carried out.

III. Result and Discussion

The finite element analysis (FEM) method is used for engineering problems that cannot be solved by an exact solution/analytical solution. The essence of FEM is to divide an object to be analyzed into several parts with a finite number [11]. These parts are called elements where each element is connected to each other by nodes (nodes). Next, a mathematical equation is built which represents the object. The process of dividing an object into several parts is called meshing.

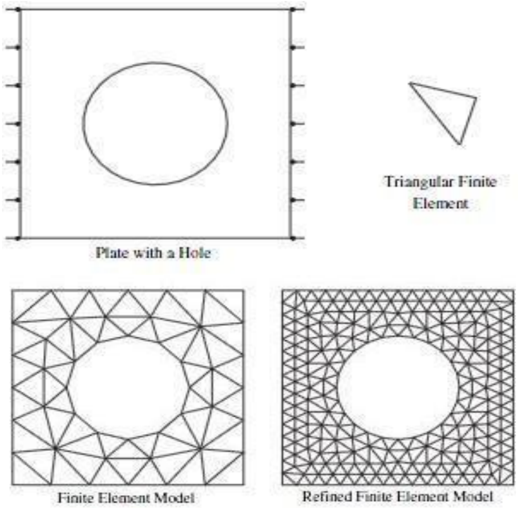

Fig. 1. Plate meshing [15]

The basis of the FEM approach is described in detail in Figure 1. Figure 1 is a visualization of a plate whose temperature distribution is to be searched. The plate geometry in the mesh is divided into small triangular parts to find a solution in the form of plate temperature distribution. Basically, this case can be solved in a direct way, namely the heat balance equation. However, complex geometries such as engine block require FEM method to find the temperature distribution [14].

The basic steps in finite element analysis according to Fish and Belytschko [15] include several phases, namely as follows:

A. Processing phase

The processing phase consists of the following steps:

1. Making and determining the area to be solved with finite elements, then proceeding with the breakdown of the problem into elements and nodes.
2. Construct the assumption of function form to describe the physical properties of an element; as a continuous function approximation that is assumed to describe the solution of an element.
3. Formulation of an equation for an element.
4. Unification of elements to present the whole problem to form a discretize global stiffness matrix.
5. Apply boundary conditions, initial conditions and loading.

B. Solving Phase

The solving or solution phase aims to solve a set of linear or non-linear algebraic equations quickly to obtain node results such as displacement values at different nodes or temperature values at different nodes in a heat transfer problem [16].

C. Polynomial Interpolation

The approximation of a continuous function in the finite element method is carried out on each element with a linear polynomial (simplex element), two-degree polynomial (multiplex element) or three-degree polynomial (complex element). The two-dimensional simplex element is a triangle with the vertices i, j, and k which are counterclockwise.

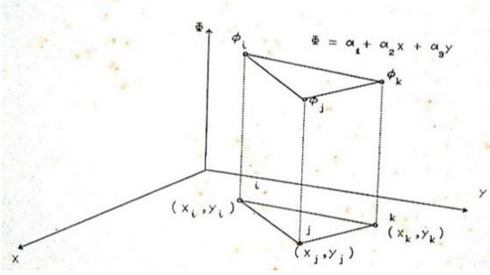
Fig. 2. Two-dimensional simplex element

Polynom interpolation: $\varphi = \alpha_1 + \alpha_2 x + \alpha_3 y$……..(1)

With the requirements:

$\varphi = \varphi_i$ on $x = x_i$ and $y = y_i$

$\varphi = \varphi_j$ on $x = x_j$ and $y = y_j$……………………(2)

$\varphi = \varphi_k$ on $x = x_k$ and $y = y_k$

Substitution (2) to (1)

Seepage flow 2-D

The determination of seepage (graphically) requires first identification of the flow line and the equipotential line. The flow line is the line that will be traversed by water seeping into the ground from upstream to downstream. A flow line can be drawn at any point where water begins to seep. Each flow line has the same k value [20].

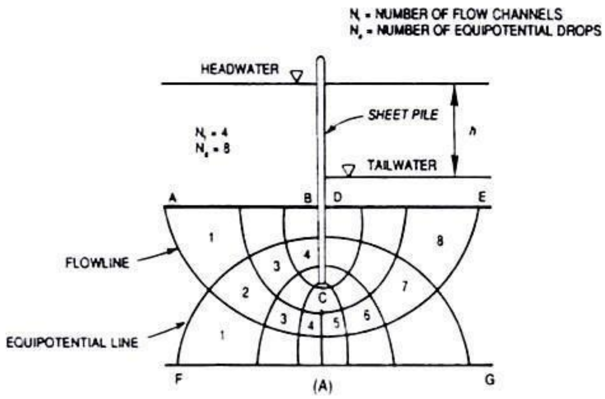

Fig. 3. Flownet of sheetpiles on the porous layer [21]

q = Kh Nf = Kh 4 = Kh

Seepage of water in the soil occurs in all directions, not only vertically or horizontally, and the amount of flow is not the same for each cross-section under consideration. Reviews are generally carried out for soil conditions with steady state flow, namely flow under conditions with assumptions that include saturated soil, constant pressure gradient, constant soil mass, and constant flow velocity [22, 23]. Element A is in the form of a cube as shown below with edges dx, dy, dz and lies in steady state flow.

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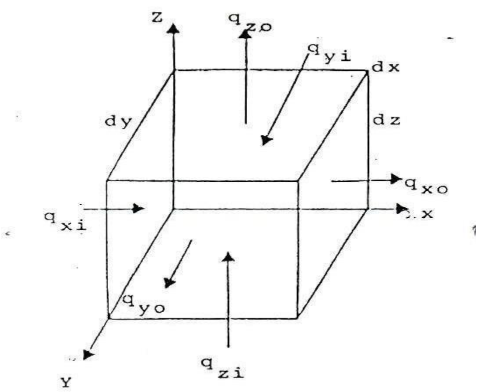

Fig. 4. Theoretical concept of 3-D flow network [20]

Based on the results of physical modeling and data analysis, the results of the design of the embankment dam are as follows:

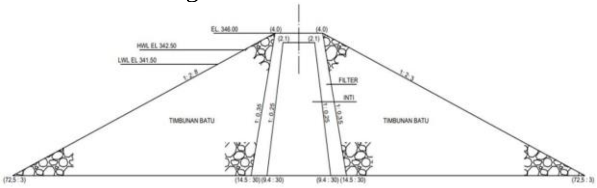
Fig. 5. The visualization of the core of embankment dam

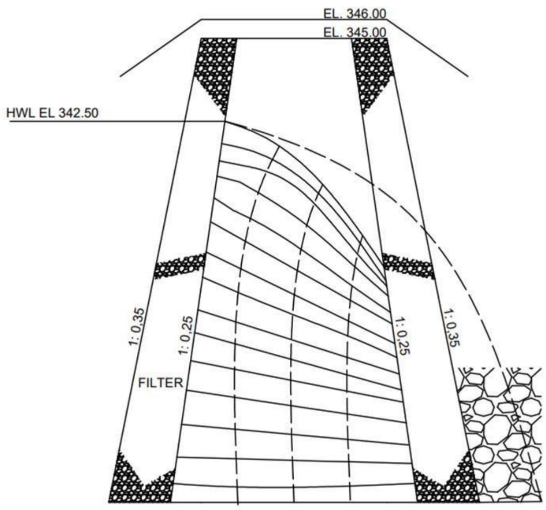

Fig. 6. Dams with seepage flow lines

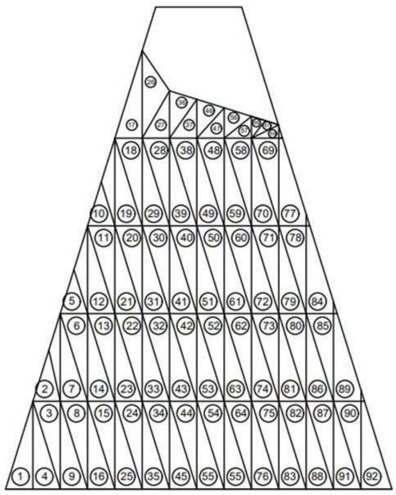
Fig. 7. Flownet diagram of the dam core

Iteration method is necessary to solve partial differential equations for 3-D flow. Numerical solutions are often performed using Finite Different or Finite Element Method 2-D and 3-D. This method requires sophisticated computer programs and requires experienced engineers. Most seepage problems in a dam can be solved using 2-D analysis, sometimes with a hand-drawn flownet. However, complex seepage problems require 3-D analysis. The design of the embankment type dam model was made in a hydraulics laboratory with a scale ratio of 1:1000. In addition, variables of discharge and pressure variations are used in the dam body. Furthermore, a seepage analysis on the dam is carried out using laboratory test materials. The results of the seepage analysis are continued with a mathematical model, namely Finite element and the results will be processed with software from electronics. The end result of this process is a generally accepted equation; can be used on all embankment type dams.

IV. Conclusion

The analysis of the finite element method of the dam results in the conclusion that the finite element method can produce a free surface line (seepage flow line) which is better than the casagranda method. In addition, the analysis carried out on each element is recommended using the results of the calculation of the flownet diagram method.

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