CFD-2D COMPUTACIONAL MODELING OF DRAINAGE SYSTEMS FOR SOLAR FARM

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Introduction

The energy transition, driven by the need to replace or complement the fossil fuel foundations of the energy matrix with sustainable sources, has become a major challenge for engineers and entrepreneurs worldwide (Figure 1).

Figure 1. Solar Farm

The lack of a specific methodology of drainage system for photovoltaic plants can result in several problems, such as erosion, siltation, and soil instability (Figure 2). This can jeopardize the entire investment and cause environmental damage to the surrounding áreas.

Figure 2. Soil instability and erosion (LANCASTER, 2023)

This study developed a CFD-2D analysis of a solar power plant drainage system using HEC-RAS software. The results were compared with traditional methodology to demonstrate the efficiency and cost reduction achieved.

Methodology

Rational Method Calculation

Surface runoff was calculated using the Rational Method with data from a DTM generated by aid of Civil 3D and QGIS. The 100 ha area was divided into 72 sub-basins to compare and validate results against the 2D numerical model.

Fundamental Equations and their CFD-2D Formulation

Mass Conservation - Continuity Equation

This equation states that mass cannot be created or destroyed. For a control volume, the rate of mass accumulation is equal to the net mass flux entering and leaving to the control volume. The differential equation for a 2D incompressible fluid is (eq. 1):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \text{(eq. 1)}$$

Where (u) and (v) are the velocity componnts in the (x) and (y) directions, respectively. The Continuity Equation principle is required for any flow dynamic analysis.

Navier-Stokes Equation and Saint-Venant Equation

Derived from Newton's Second Law, this equation states that the rate of change of a fluid's momentum is equal to the sum of the forces acting on it, both surface and gravitational forces. For an incompressible fluid, the Navier–Stokes equations in the X, Y and Z directions are:

$$\rho g_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = \rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) \quad \text{(eq. 2)}$$

$$\rho g_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) = \rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) \quad \text{(eq. 3)}$$

$$\rho g_z - \frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) = \rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) \quad \text{(eq. 4)}$$

Where:
(t) is time,
(p, u, v, w) are the unknown variables,
(gx, gy and gz) are the components of gravitational acceleration.
In drainage systems, based on open-channel and floodplain flow, the water depth Z is small compared to the X and Y directions. It leads to the two-dimensional analysis, based on the Shallow Water Equation – SWE, known as the Full Saint-Venant Equation (BALZANO, 1998), which is applied in HEC-RAS and other hydraulics software.

CFD-2D Modeling

The simulation was carried out in HEC-RAS 2D using a detailed digital terrain model to create a mesh of 50,000 points. For validation, the area was divided into 72 sub-basins, but the hydraulic calculation considered the entire 100 ha basin.

Rational Method

The Rational Method is widely used to estimate the peak surface runoff in watersheds during intense rainfall events, based on rainfall intensity, time of concentration, and contributing area.

$$Q = 0{,}0028 \times C \times I \times A$$

Q – Runoff flow (m3/s)
C – Runoff coficient
I – Precipitation intensity (mm/h)
A – Contribuition area (ha)

Results and Conclusion

Flood water depth - Without a drainage system

Water depths in critical areas exceeded 75 cm, while regions above 30 cm the project's maximum limit were highlighted in yellow, indicating the need for drainage interventions (Figure 3). Surface runoff velocities were mostly below 0.4 m/s, but some points exceeded 0.7 m/s, requiring energy dissipation measures to prevent soil erosion.

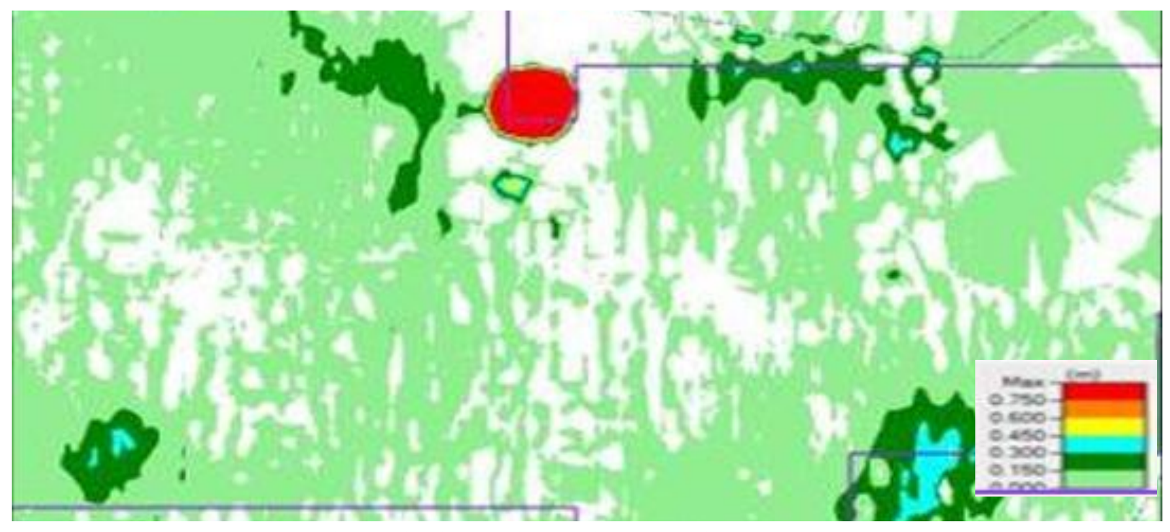

Figure 3. Scenario 1: Without drainage system

Flood water depth – Traditional drainage calculation

A two-dimensional CFD-2D simulation, considering the drainage network calculated by the traditional method, showed that all water depths were below 30 cm, which was the main objective of the project (Figure 4). On the other hand, the computational analysis also showed that some gutters could be eliminated or reduced.

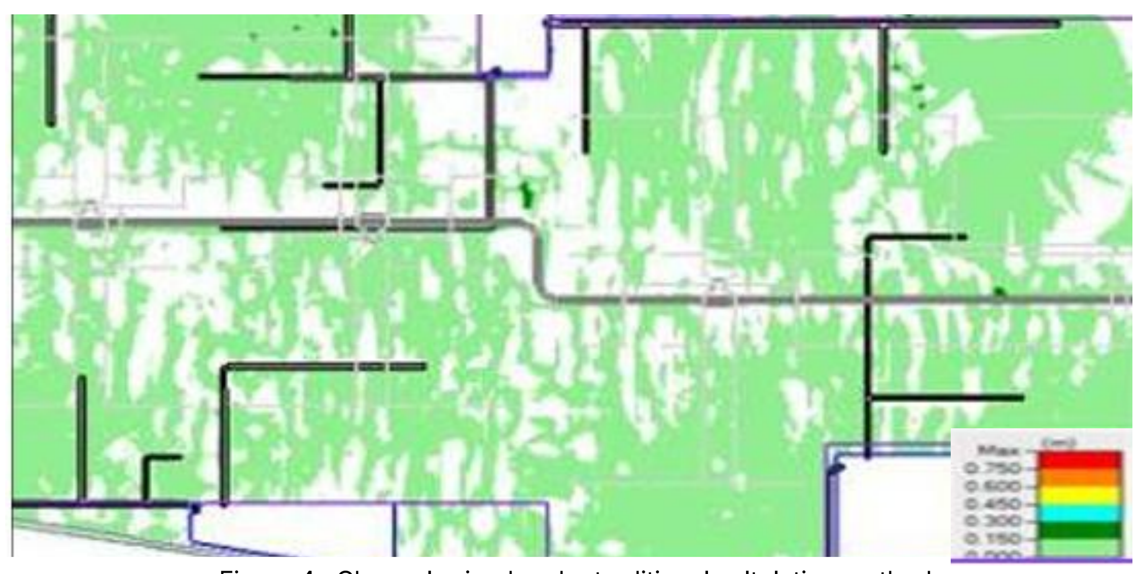

Figure 4. Channels sized under traditional caltulation method

Flood water depth – CFD-2D drainage calculation

To optimize the project, some gutters were eliminated and the length of the channels was reduced in areas where the simulated water depth was less than 10 cm (Figure 5). All cross-sectional dimensions of the channels remained unchanged. This adjustment resulted in a net reduction of 938 m, representing 22.54% in the total channel length compared to the design calculated by the traditional method.

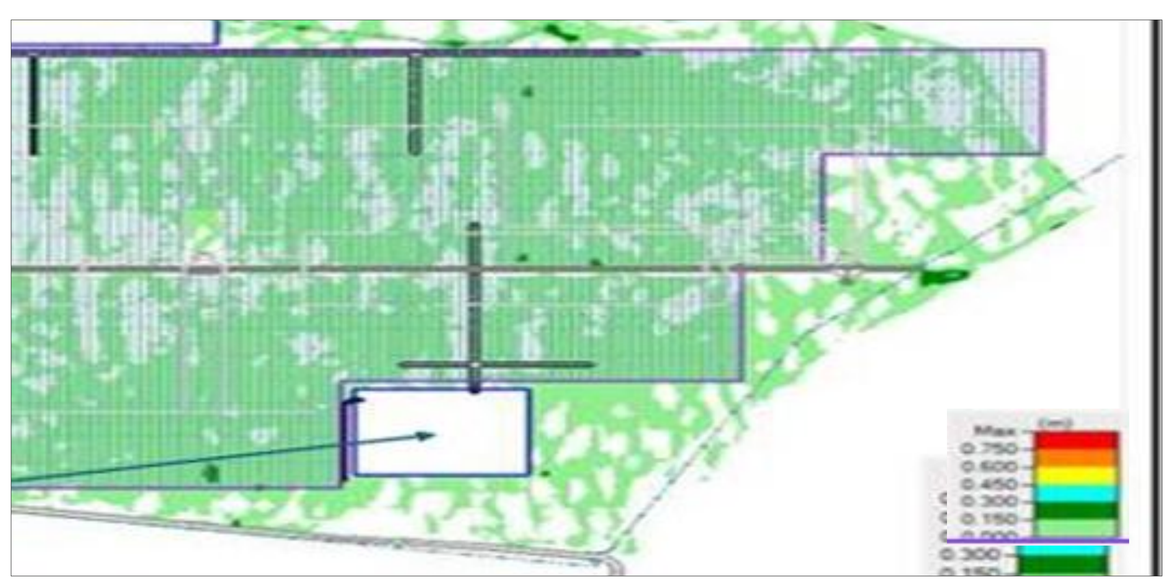

Figure 5. Channel sized under CD-2D calculation with reduced drainage gutters

Conclusion

- 22.54% shorter drainage gutters = major cost savings.
- Higher precision identified critical points and optimized infrastructure.
- Sustainable and efficient Drainage System .

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