NUMERICAL MODELING METHODOLOGY AND TECHNIQUES FOR THE EXTERNAL FLOODING ANALYSIS OF ASCÓ AND VANDELLÓS II SPANISH NUCLEAR POWER PLANTS, DURING STRESS TESTS

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ABSTRACT: Considering the accident occurred at Fukushima Daiichi Nuclear Power Plant in Japan, the European Council of March 24-25, 2011 stated that “the safety of all EU nuclear plants should be reviewed, on the basis of a comprehensive and transparent risk assessment (“stress tests”)”. In this context, the WENRA (Western European Nuclear Regulators Association) established the technical contents of the stress tests and how they should be applied to all nuclear facilities across Europe. One aspect of the stress tests is related to External Events. This includes fluvial flood risk or severe local precipitation on the plant site. The purpose of this article is to describe the methodology used by ANAV, the operator of Ascó and Vandellòs II NPPs, for assessing and improving the safety threshold of its plants beyond their design basis, in order to comply with WENRA stress tests specifications concerning External Flooding Events. The analysis begins with the identification of the local environmental factors that can cause a plant flood and all their combinations. Subsequently, the article describes the numerical modeling techniques and the main hypotheses used to represent the consequences caused by a Local Probable Maximum Precipitation (PMP) to Structures, Systems and Components of the Nuclear Plant. The results of the analysis have led to adopting additional measures to increment the Hydraulic Risk safety threshold for the two Spanish Nuclear sites in Catalonia.

Key Words: PMP, Nuclear Safety, Stress Tests.

1. DEFINITIONS AND ABBREVIATIONS

ANAV: Operator of Ascó and Vandellós II Nuclear Power Plants.

CSN: Spanish Nuclear Regulator (Consejo de Seguridad Nuclear)

DTM: Digital Terrain Model, the bare ground surface without any objects (like plants and buildings). A Digital Surface Model (DSM) represents the earth's surface and includes all objects on it.

EE: External Events. All those Events whose cause is external to all systems used during normal and emergency operations. This includes plant floods caused by river flooding or severe local precipitation on the plant site.

ES: External System. A drainage system not been part of the nuclear facility

ICC: Catalan Cartography Institute (Instituto Cartográfico de Cataluña)

IS: Internal System. A drainage system been part of the nuclear facility.

NPP: Nuclear Power Plant.

Esplanade: Portion of terrain that includes Nuclear Facilities

PMF: Probable Maximum Flooding: A Flooding as consequence of a PMP.

PMP: Probable Maximum Precipitation. The greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year with not allowance made for long-term climatic trends.

RT: Risk Threshold. The minimum gap existing between the NPP defense measures protecting SR SSC and the maximum probable flooding level.

SA: Severe Accident. An accident that involves Safety Relevant Structures, Systems and Components (SR SSC).

SR: Safety Relevant.

SSC: Structures, Systems and Components.

2. INTRODUCTION

Considering the accident occurred at Fukushima Daiichi Nuclear Power Plant in Japan, the European Council of March 24-25, 2011 stated that “the safety of all EU nuclear plants should be reviewed, on the basis of a comprehensive and transparent risk assessment (“stress tests”)”. In this context, the Western European Nuclear Regulators Association (WENRA, 2011) established the technical contents of the stress tests and how they should be applied to all nuclear facilities across Europe. One aspect of the stress tests is related to EE (ANAV, 2010 and 2011).

3. OBJECT

The purpose of this work is to explain the methodology used to identify critical events and combinations thereof, in order to evaluate the flooding risk threshold due to EE for Ascó and Vandellòs II NPPs.

The Evaluation has been set up in order to achieve four main goals:

- ☐ Identifying buildings containing Safety relevant Structures, System and Components (SR SSC) that are vulnerable to flooding
- ☐ Identifying the flooding level that the NPP can sustain without suffering a Severe Accident.
- ☐ Establishing whether the current hydraulic defences of the NPP could be improved
- ☐ Establishing whether additional hydraulic defences can be adopted.

4. IDENTIFICATION OF THE CRITICAL EVENTS AND THEIR COMBINATION

SR SSC should be designed to withstand the effects of a PMF without losing any of the safety related functions in order to take and maintain the NPP in to a safe state (CSN, 2010). Design criteria shall include the following aspects:

- ☐ Extreme Natural Phenomena historically registered in the NPP and its surroundings. An adequate threshold shall be used to take into account deficiencies in historical data in terms of quality, quantity and recording time.
- ☐ Realistic combinations of natural phenomena effects acting on NPP for normal and accident operational conditions shall be considered.
- ☐ The importance of each SSC in terms of safety shall be taken into account.

For instance in case of an NPP close to a river or water path (i.e ASCÓ NPP) critical flooding that shall be taken into account for design base are (USNRC, 1977 and 1991):

- ☐ Hydrometerologic flooding due to an increment of river depth.

- ☐ Flooding due to landslides or seismic effects in upstream dams.

Nevertheless, even in case the NPP is built at an adequate elevation that can guarantee protection against river flooding, local precipitation shall be considered as a critical event.

Each one of the cases mentioned above could represent the upper limit of every flooding realistic possible combination.

A methodology to estimate the PMP is explained in *Standards for determining design basis flooding at power reactor sites* (ANS, 1976), which in turn refers directly to the *Manual for estimation of Probable Maximum Precipitation* (WMO, 1973).

Current knowledge concerning storm events and precipitation forecasting are for the accurate evaluation of extreme precipitation limits. PMP estimation shall be considered, at the moment, as an approximation because it depends strongly of the accuracy and quantity of available data. Moreover PMP determination procedures could not be standardized, because strictly related of a quantity of parameters such as available data, basin size and setting, surroundings topography, local weather and storm events.
The majority of the procedures but one for PMP estimation are based on hydrometerological methodologies consisting in humidity maximization and its transposition to the observed storm.
The only exception is the statistical procedure that is the most frequently used for PMP estimation due to its ease of use. Detailed descriptions for PMP estimation methodologies are beyond the scope of this work and they can be consulted in specific manuals (WMO, 1973).
For this scope, rain information (Probable Maximum Precipitation (PMP) and its related flows considering characteristics of the basins of the rivers) was based on the studies developed by Polytechnic University of Catalonia (UPC, 2012).

5. STUDY METHODOLOGY

The methodology of this study is based on the phases as descripted below.
It is important to stress that the entire process was been constantly referred to nuclear quality standards and nuclear safety requirements.

5.1 Phase 1: Input data collection

The first step has concerned the review of hazard data contained in the plant licensing documentation, as well as plant drainage schemes and “as built” drawings supplied by ANAV.
The initial information has been integrated by a topographic survey of the site and specific plant walkdowns in order to dispose of a more accurate dataset of the drainage network and urban elements considered relevant for the analysis (such as gullies, steps, barriers..).
A topographic survey of the river section also has been carried out.
NPPs surroundings have been characterized using existing cartography in order to identify hydrological basins and watershed that could affect Nuclear Site Esplanade in case of flooding.
Meteorological data from the local meteorological station were compared with Governmental Data series.

5.2 Phase 2: Data preparation

Data have been processed to create the basis for hydraulic calculation.
Using ANAV plant documentation, all buildings hosting SR SSC that could be vulnerable in case of flooding, have been identified.
A Hydrologic Analysis for basins and watershed has been set up using Curve Number infiltration Model (USDA, 1986).
A local value for PMP has been calculated using the World Meteorological Organization method (WMO, 1973).
A site esplanade rendering and meshing has been generated from available cartographic data and the results of the topographic survey.

5.3 Phase 3: Rivers and drainage network analysis

A 1D hydraulic analysis has been implemented through an iterative process, in which the results of the first simulations have been used to produce the boundary conditions for a second simulation in cases where external and internal systems could influence each other.
As a result of the hydraulic analysis for drainage network and rivers, an estimation of the flooding volume has been obtained.

5.4 Phase 4: Risk threshold estimation

Using the previous flooding volume estimation, a 2D hydraulic analysis has been performed based on esplanade site 2D meshing.
A comparison has been made between the site area water level and the elevation of relevant building entrances, in order to understand if flooding could reach the interior of the buildings hosting SR SCC.
As result, a risk threshold has been estimated.

5.5 Phase 5: Hydraulic defenses design

For those zones of the esplanade where the risk threshold was not deemed satisfactory, risk mitigation measures have been designed. Numerical models have been updated with networks at improved condition and new simulations have been run. The final results have been submitted first to ANAV internal inspection and finally to the Spanish Nuclear Regulator (CSN) inspection.

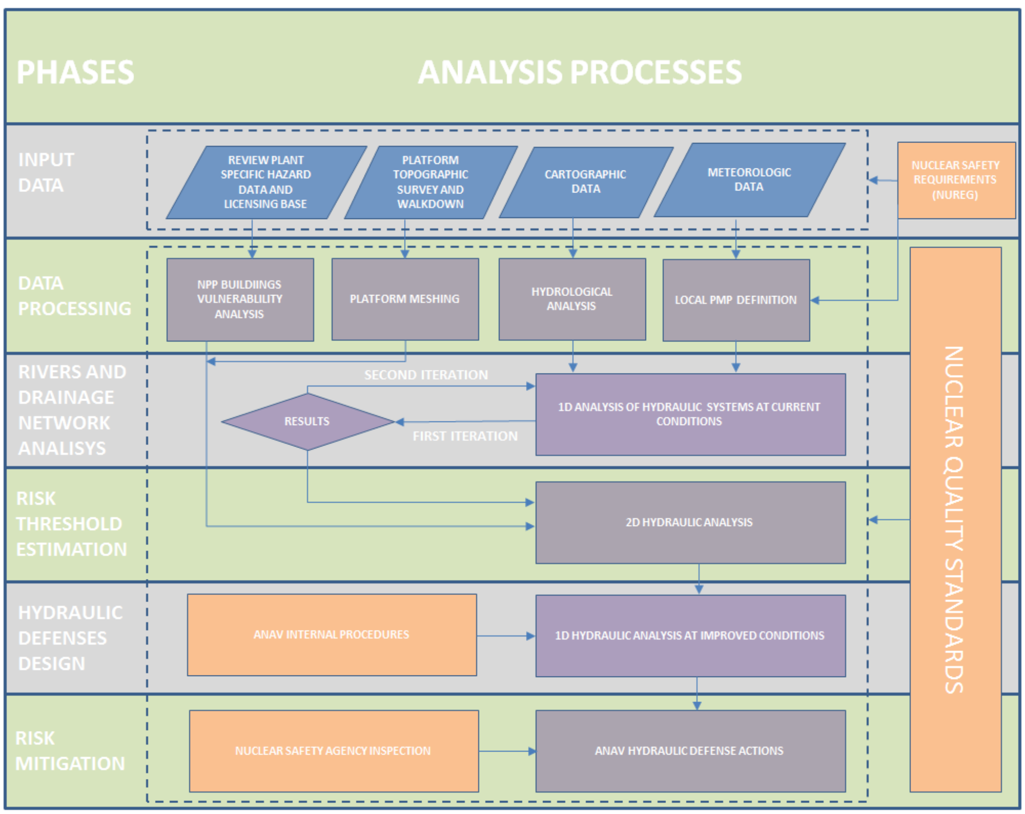

Figure 1: Scheme of analysis methodology

6. INPUT DATA

The following input data have been used for the development of the hydraulic models:

- ☐ Cartographic charts (3D). Scale 1:1000.

  The cartographic charts are developed by Instituto Cartográfico de Cataluña (ICC), referred to ETRS89 geodesic system (GRS80 ellipsoid). Elevations are referred above mean sea level in Alicante.

- ☐ Cartographic charts (3D). Scale 1:5000.

  The cartographic charts are developed by Instituto Cartográfico de Cataluña (ICC), referred to ED50 geodesic system. Elevations are referred above mean sea level in Alicante

- ☐ Topographic survey. Scale 1:200 and 1:500.

  The topographic survey considered all existing structures, culverts and drainage system located in the area of influence and relevant elevations in river sections.

- ☐ Ascó and Vandellòs II Power Stations Project Drawings.

  ANAV project drawings have been used as the starting point to identify drainage, sewerage and other existing underground pipes systems. The drainage network has been checked against the topographical survey of the existing drainage network. Project drawings were reviewed with the personnel of the maintenance department of both nuclear power stations and other related staff if necessary.

- ☐ License Basis.

  License basis documents were consulted, in order to take into account design considerations of the nuclear power stations related with drainage systems.

- ☐ Probable Maximum Precipitation (PMP).

  Rain information was based on the studies developed by Polytechnic University of Catalonia (UPC): Evaluation of PMP with local meteorological data from Vandellòs II Power Nuclear Station (UPC, 2012) and Evaluation of PMP with local meteorological data from Ascó Power Nuclear Station (UPC, 2012)

- ☐ Boundary conditions.

  The discharge boundary condition for Ascó Nuclear Power Station is represented by the Ebro River. Elevations of the river were extracted from data submitted by Hydrographic Authority (CHE: Confederación Hidrográfica del Ebro). Previous studies related to Ebro River and its flood levels developed by ANAV in 1986 have also been considered.

  For Vandellòs Nuclear Power Station, a free discharge conditions to Mediterranean Sea has been defined, since the difference between above mean sea level and discharge points elevations creates a hydraulic disconnection condition.

- ☐ Basin characterization

  Geological data is based on the available information published by Instituto Cartográfico de Cataluña (ICC, 2007)

  Soil uses are based on the available information published by Departament de Medi Ambient i Habitatge, Generalitat de Catalunya (GCDMAV, 2009)

7. DRAINAGE NETWORK HYDRAULIC ANALYSIS USING EPASWMM

EPASWMM software (EPA,2005) has been used for drainage network analysis. The software includes modules for calculating runoff (hydrological module) and network hydraulic calculation (transport module).

EPASWMM allows the insertion of network geometry using a nodes and connections scheme to represent drainage network elements such as wells and pipes.

The site Area has been divided in sub basins each one connected to a node of the network.

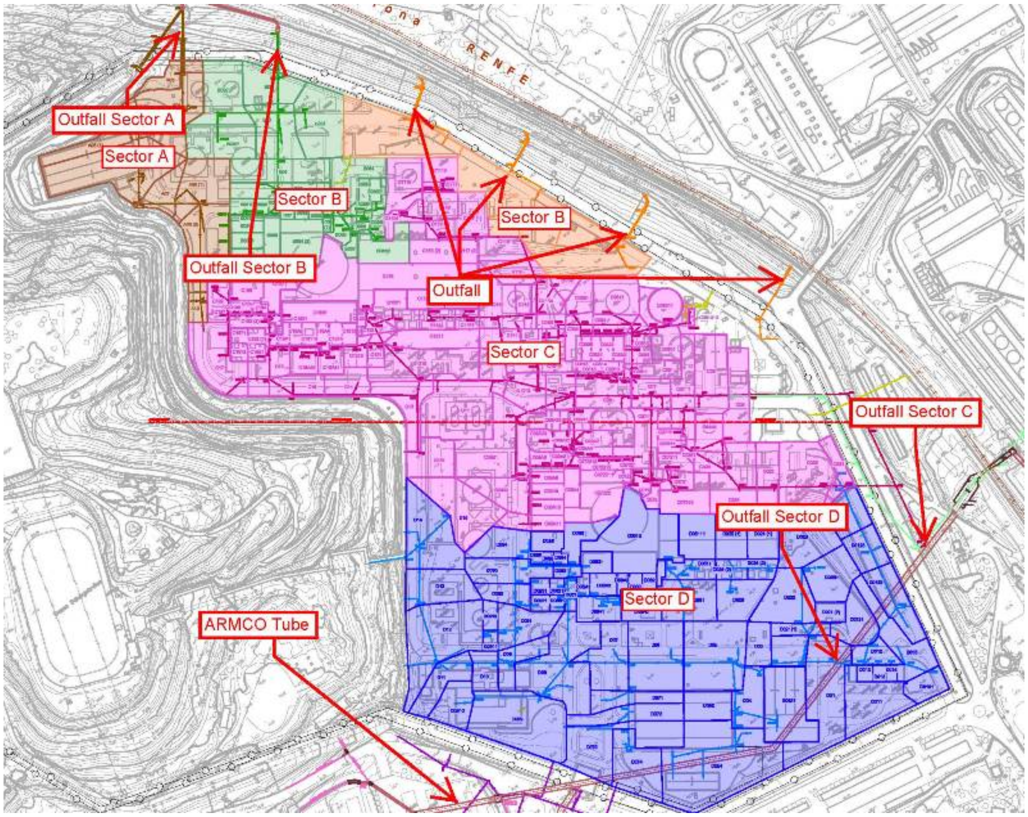

Figure 2: An example of Subbasin definition for Ascó NPP Esplanade

Subbasins have been defined in EPASWMM and the Curve Number routine has been selected as infiltration model.

Precipitations have been inserted into the model using a triangular hyetograph with a centered peak, which maximizes circulating flows in a network characterized by short travel time such as those under study.

The hypothesis of 100% water basins runoff catchment by superficial drainage elements (ideal) has been assumed, leading to a conservative condition by the prospective of flow circulating through the network.

Pipe roughness has been defined using Manning coefficients. Existing concrete pipe has been characterized by a Manning coefficient between 0.012 and 0.015 depending on the actual condition. 0.01 and 0.024 values have been adopted for plastic pipes and corrugated steel pipes respectively.

Buried service galleries have been included in the network model because they are connected with the drainage system and acting as discharge control or water volume buffer in case of flooding.

Electrical galleries have been considered completely water-tight and for this reason they have not been included in the drainage network.

The Dynamic Wave routine has been used as transport module. Dynamic Wave uses De Saint Venant equations in their complete form. This routing allows representing pressurized flow when the conduit maximum capacity is exceeded and considers dynamic effects such as backwater and reversal flows. The inertial term in the Saint Venant Equations has been treated with Dampen algorithm in order to reduce its importance as flow approaches the critical state.

For boundary conditions definition, cases where external and internal systems could influence each other have been taken into account.

8. RIVER HYDRAULIC RISK ANALYSIS USING HEC-RAS

River hydraulic risk analysis and river discharge capacity improvements have been studied using the Hec Ras software (U.S. Army Corps of Engineers, 2011) due to their markedly mono dimensional character.

The assumptions made for the scope of this work are listed in the following:

- ☐ Steady flow i.e. no variation in time for water depth or velocity.
- ☐ Gradually varied flow i.e. pressure´s hydrostatic distribution
- ☐ Unidirectional flow i.e. velocity vector direction follows the flow although Hec Ras take into account laminate and storing effects on the peak flow.
- ☐ No erosive or sedimentation processes have been taken into account
- ☐ Calculation process has been based on the Standard Step Method
- ☐ Numerical resolution scheme has benn based on Preissmann Method.

Boundary conditions have been adapted to site conditions. For cases in which external and internal systems could influence each other, a boundary condition has been set using iterations as explained in section 5. The PMF has been used as input flow.

Manning coefficients are based on the characteristic of each section of rivers or modeling surface.

9. CARTOGRAPHIC DATA PROCESSING USING ARCGIS

Cartographic and Topographic have been processed using ArcGIS (ESRI, 2010).
Data classified as Points, Polylines and Polygons, contain X, Y and Z spatial information.
An Esplanade DTM has been generated in ArcGIS using a Triangular Irregular Network (TIN) modality using Delaunay triangulation method. A TIN is a fast and effective way to generate a digital terrain model (DTM). ArcGIS allows the visualization of both the topographic data and the resulting TIN. This can help the analyst validate the generated TIN surface and, if needed, make some manual adjustments, edit and/or correct some outlier data. The challenge was to easily be able to add the existing building footprints to the TIN without the creation of noisy triangle cells. Distorted triangles (Figure 1) fill the DSM with no existing volumetric features that could seriously distort the final hydrological model.

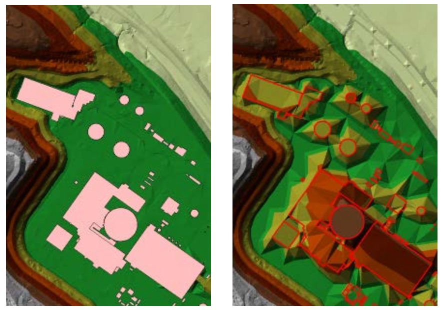

Figure 3. On the left, the DTM with building polygons. On the right the building footprint added to the TIN DTM, generating a DSM with noisy triangles

To avoid such issue, a routine[1] developed by Esri for this specific purpose was used. This code easily enabled the analyst to add the buildings to the TIN with their near-vertical walls, generating a near to reality DSM including all the volumetric infrastructures (Figure 4).

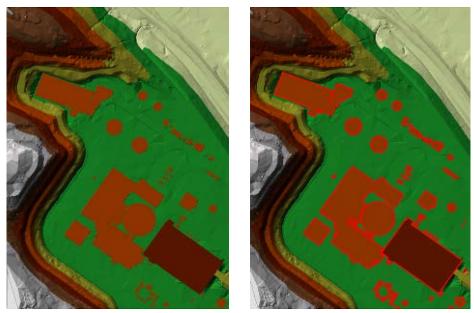

Figure 4: Result of the DSM using the cited Esri Code. On the right, existing infrastructure limits

Once the final DSM is validated, it can be exported to a grid file used by IBER 2D[2] to build the mesh.

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1 Add Buildings to TIN http://edn.esri.com/index.cfm?fa=codeExch.sampleDetail&pg=/arcobjects/9.1/Samples/3D_Analyst/Tin_Editing/Add_Buildings_to_Tin/Add_Buildings_To_Tin.htm

2 Iberaula.http://www.iberaula.es/web/index.php

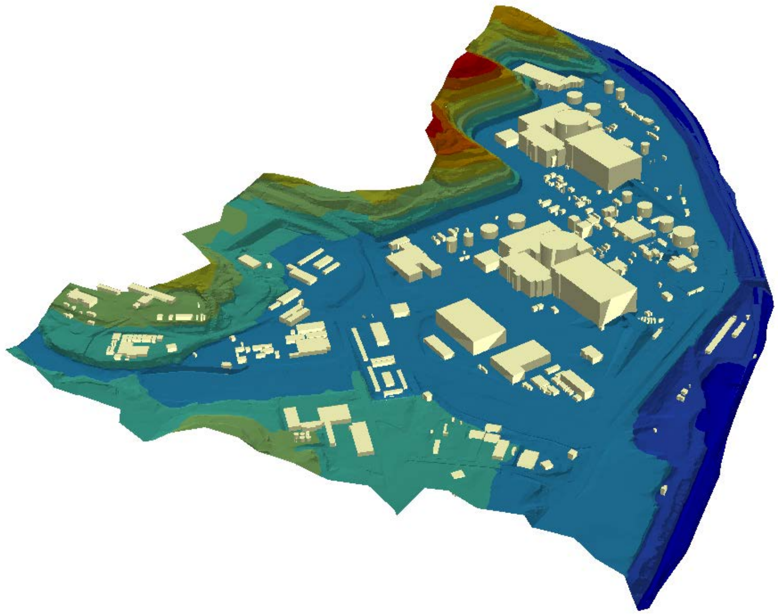

Figure 5: Ascó Esplanade DTM generated by ArcGIS

10. HYDRAULIC RISK ANALYSIS OF THE ESPLANADE USING IBER 2D

In order to know the flooding water elevation for every point of the esplanade, a 2D numerical calculation has been performed. The 2D mesh model includes urban elements internal to the double fence and some neighboring areas.

The hydraulic calculation has been run in IBER 2D (*). This software allows the resolution of Saint Venant Equations in their complete form, for a 2D problem (shallow waters). The main characteristics adopted for the numerical scheme are the following:

- ☐ Structured Meshes
- ☐ Hydrodynamic equation resolution with high resolution decentered scheme such as Roe
- ☐ Decentered treatment for bottom slope
- ☐ Centered treatment for others terms.

A structured mesh has been implemented in IBER starting from the TIN previously defined in ArcGIS (see section 9). This specific mesh has proven to be the most accurate in order to represent abrupt direction changes, such as between esplanade and building walls.

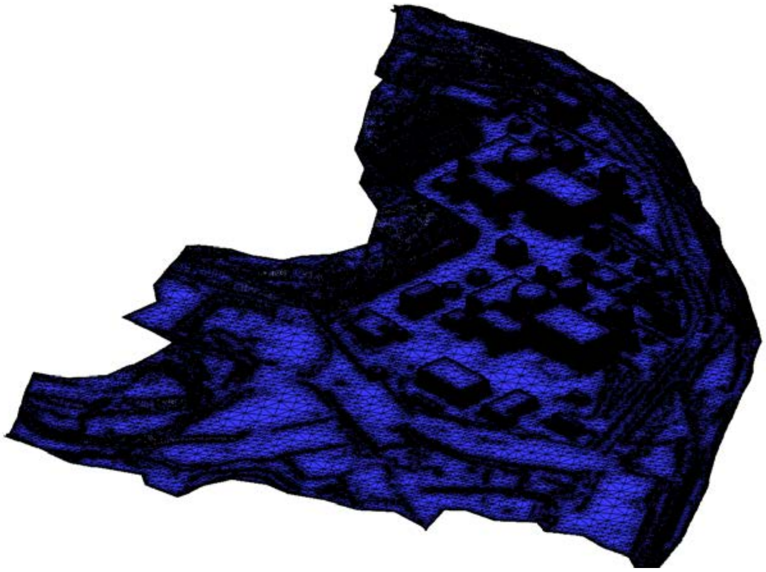

Figure 6: Ascó Esplanade Mesh generated by IBER 2D

Flooding hydrographs have been inserted in the model as precipitation rainfall in relation to outfall nodes position.
A zero elevation overflow boundary condition has been set for the external perimeter of the model.
An internal IBER routine has been used to automatically assign a Manning value to every element of the mesh.
Manning Values that has been used to characterized different urban areas are indicated in the Table 1.

Type of surface	Manning
Pavement	0.150
Green areas	0.080
Rivers	0.025
Sparse vegetation	0.120
Brush land	0.050

Table 1: Manning coefficient for different types of surface

A high Manning value for pavement has been used to take into account urban elements whose size was too small to be included into the model.
The initial condition of the cell water level has been set to zero (initial dry condition).

11. IMPLEMENTATION OF HYDRAULIC DEFENSES

The hydraulic risk evaluation leads to design additional hydraulic defenses for NPPs in order to increase the safety threshold.
The design approach follows the criterion “Measures with Minor Impact to Nuclear Facilities and Environment are considered First” as described in Figure 7.

Actions have been classified as priority and secondary actions and have been implemented in order of importance.

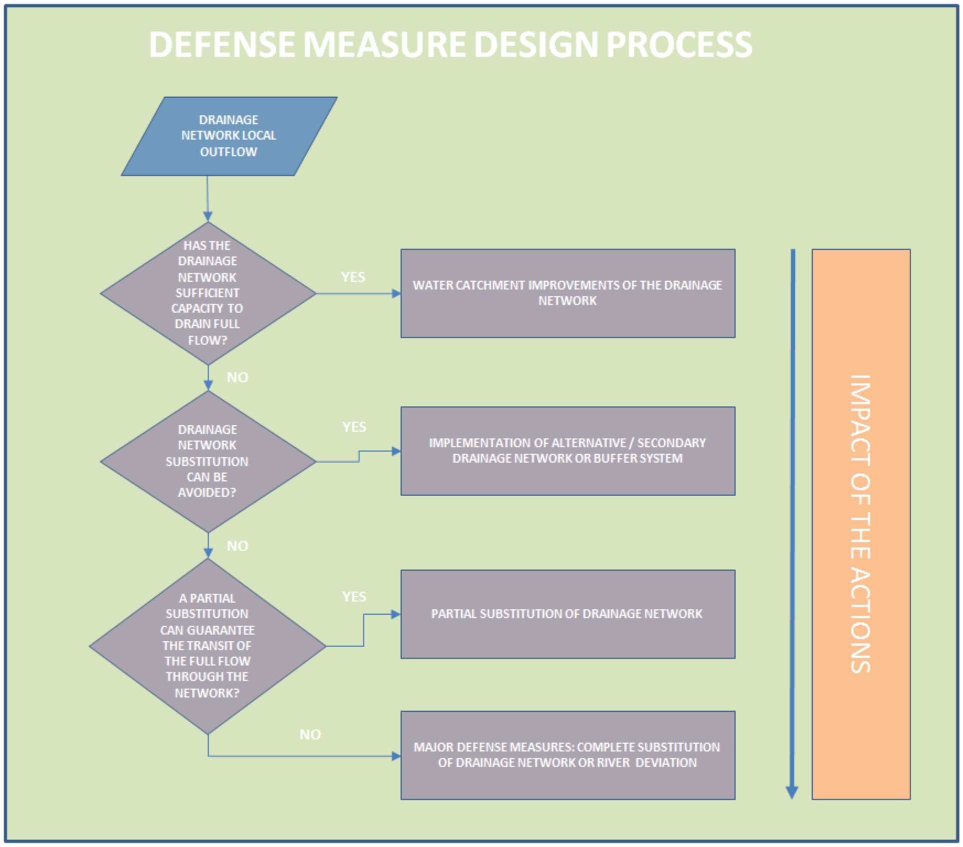

Figure 7: Defense measure's design process.

12. CONCLUSIONS

Considering the accident occurred at Fukushima Daiichi Nuclear Power Plant in Japan, the European Council of March 24-25, 2011 stated that "the safety of all EU nuclear plants should be reviewed, on the basis of a comprehensive and transparent risk assessment ("stress tests").

Following Nuclear Quality Requirements and Standards, the hydraulic risk threshold for Ascó and Vandellòs II NPPs has been evaluated considering different combinations of critical events, such as river flooding and intense site precipitations. A local PMP has been estimated.

In order to answer the Stress Test requirements, a study methodology has been developed, consisting of a 1/2D iterative hydraulic calculation method that leads to the estimation of a safety threshold for Ascó and Vandellos NPPs.

From the analysis of the results, hydraulic defenses have been designed in order to increment the existing safety threshold.

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