PROJECT INFORMATION

Project Title: Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain
Acronym: SYNER-G
Project N°: 244061
Call N°: FP7-ENV-2009-1
Project start: 01 November 2009
Duration: 36 months

DELIVERABLE INFORMATION

Deliverable Title: D5.4 – Systemic vulnerability and loss for water and waste-water systems
Date of issue: December 2011
Work Package: WP5 – Systemic vulnerability specification
Deliverable/Task Leader: Aristotle University of Thessaloniki
Reviewer: UILLINOIS

REVISION: Final

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Abstract

This deliverable aims to specify vulnerability methodologies that can be applied to seismic risk analysis of water supply (WSS) and waste water (WWN) networks. In the first section is briefly reported for reference the taxonomy for the components of a WSS and WWN. Details for the typologies, fragility analysis models, damage states definitions and performance indicators of the different elements are given in deliverable D3.5 (Alexoudi et al 2010). The performance measures of the two networks are further described in deliverable D2.5 (Kakderi et al 2011). In the next section the general framework for the systemic vulnerability analysis as well as the interdependencies of WSS and WWN are described. The last section presents the software implementation and the structure of classes and sub-classes for the WSS.

Keywords: connectivity, flow analysis, water system, waste water network
Acknowledgments

The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 244061.
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1 Taxonomy of water supply and waste water networks

1.1 GENERAL DESCRIPTION

*Potable water supply* is necessary for drinking, food preparation, sanitation, fire-extinguishing etc. Water (which may be non-potable) is also required for cooling equipment.

A water supply network consists of transmission and distribution systems:

- Transmission system stores “raw” water and delivers it to treatment plants. Such a system is made up of canals, tunnels, elevated aqueducts and buried pipelines, pumping plant and reservoirs.
- Distribution system delivers treated water to customers.

The water supply system as a whole is composed of a number of point-like critical facilities (water sources, treatment plants, pumping stations, storage tanks) and of the water distribution network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system is made of: pipelines, tunnels and canals and the supervisory control and data acquisition (SCADA) sub-system.

*Waste-water system* can alternatively be called sewer network. It is comprised of components that work together to:

- Collect
- Transmit
- Treat
- Dispose of sewage

The waste-water system as a whole is composed of a number of point-like critical facilities (treatment plants, pumping stations) and of the distribution network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system is made of: pipelines, tunnels.

For obvious reasons pipes usually follow the plan layout of the road network. From a topological point of view, WSS and WWN can be either tree-like networks or grid-like networks, as shown in Fig.1.1. In tree-like networks whenever an interruption (due to failure or maintenance) occurs in a point of the network, the whole downward portion of the network is out-of-service. This undesirable behaviour is avoided with grid-like networks, which are more reliable since water can flow through pipes in different directions upon changed boundary conditions reaching otherwise unserviced end-users.

The network can be decomposed into hierarchically arranged levels or orders. The first order collects all pipes in the main distribution, which follows the main roads in the area and through which the largest water volumes flow. This is usually designed as a grid-like network in order to reliably reach the second and third order networks. The latter follow the lower-order roads and
have the task of reaching as close as possible to the end-users. Mainly for economic reasons these portions of the networks are most often of the tree-type (and each of these sub-networks on one hand serves a smaller demand, thus limiting the impact of service interruption, and on the other is made up of smaller diameter pipes which can be repaired with ease).

![Fig. 1.1 Typical topological structures, grid-like (on the left) and tree-like (on the right) (Franchin et al 2011).](image)

As explained in the deliverable D2.1 “General methodology for systemic seismic vulnerability assessment” (Franchin et al 2011), components may be classified essentially in “point-like” components (critical facilities) or “line-like” (network) components respect to the geometric point of view and the approaches used for the characterization and definition of the vulnerability. According to this, water source and water treatment plants for the WSS and waste-water treatment plants for the WWS may be considered as “critical facilities”, i.e. single site-facilities whose importance for the functionality of the system (or generally more systems if they are interconnected with other networks) makes them critical, justifying a detailed description and analysis. Therefore stations, storage facilities and pipelines are considered “line-like” components, and the vulnerability methodology explained below will be referred to those components. Table 1.1 shows the networks components that are considered for the vulnerability analysis.

<table>
<thead>
<tr>
<th>Table 1.1 Water and waste-water system components</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WATER SUPPLY NETWORK (WSS)</strong></td>
</tr>
<tr>
<td>Element Code</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>WSS01</td>
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<tr>
<td>WSS02</td>
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<tr>
<td>WSS03</td>
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<td>WSS04</td>
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<td>WSS05</td>
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<td>WSS06</td>
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<td>WSS07</td>
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<tr>
<td>WSS08</td>
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<tr>
<td><strong>WASTE WATER NETWORK (WWN)</strong></td>
</tr>
<tr>
<td>WWN02</td>
</tr>
</tbody>
</table>
According to the specific case study, one or more of the components may be considered as not vulnerable. For example, at regional scale water treatment plants are the major water system components determining the functionality and serviceability of the whole network. At an urban scale, water supply from the treatment plants can be considered as constant, with the respective elements considered as non-vulnerable. In this case, the pumping stations at the supply nodes of the city are the major elements for the system’s functionality.

### 1.2 WATER SUPPLY NETWORK COMPONENTS

**WSS01 Water Source**
Includes springs, shallow or deep wells, rivers, natural lakes, and impounding reservoirs. Wells are complex components that include several sub-components: Electric power; Well pump; Building; Electric equipment. The subcomponents can be anchored or unanchored. Characteristics of wells are: capacity, depth, history of failure, hazardous materials in the area (distance < 500m), construction cost.

**WSS02 Water Treatment Plant**
Includes complex facilities, generally composed of a number of connected physical and chemical unit processes. They can be categorized by their size (small, medium or large) and by the anchorage (or not) of their subcomponents and backup power. The subcomponents are: Electric Power; Chlorination equipment; Sediment flocculation; Basins; Baffles; Paddles; Scrapers; Chemical Tanks; Electric equipment; Elevated pipe; Filter Gallery.

**WSS03 Pumping Station**
Boost water pressure in both transmission and distribution system. They can be categorized according to their size (small or medium/large) and by the anchorage (or not) of their subcomponents and backup power. The following subcomponents may be considered in a pumping station: Electric Power; Vertical/ Horizontal Pump; Building; Equipment.

**WSS04 Storage Tanks**
Can be categorized according to: type (close, open cut reservoirs); material (wood, steel, concrete, masonry); capacity (small, medium, large); anchorage (yes, no); position (at grade or elevated by columns or frames); type of roof (R/C, steel, wood); seismic design (yes, no); construction type (elevated by columns, built “at grade” to rest directly on the ground, build “at grade” to rest on a foundation, concrete pile foundation); presence of side-located inlet-outlet pipes; volume (height and diameter), thicknesses; operational function (full, nearly full, less than full).

**WSS05 Pipes**
Can be free-flow or pressure conduits, buried or elevated. Can be categorized according to: location (buried or elevated); type (continuous or segmented); material (ductile iron, steel, PVC-ABS, PE, RPM, RTM- asbestos-cement pipes, cast iron, concrete, clay); type of joints (rigid, flexible); capacity (diameter); geometry (wall thickness); type of coating and lining; depth; history of failure; appurtenances and branches; corrosiveness of the soil conditions; age; pres-
sure. Moreover, pipes can be categorized according to the type of consumer (industries, critical and commercial facilities, housing)

**WSS06 Tunnels**

Rock or alluvial tunnels. Bored, NATM (circular, petaloid section) or Cut & Cover (rectangular section). Various supporting systems (concrete etc).

**WSS07 Canals**

Free-flowing conduits, usually open to the atmosphere, and usually at grade. They tend to be larger than pipelines operated under pressure. Can be categorized according to: material (wood, steel, concrete); appurtenances and branches location; age of construction; geometrical characteristics (width, depth, capacity); section (orthogonal, trapezoid etc); inclination.

**WSS08 SCADA system**

Control and communication systems are critical for the safe and continuous conveyance of water, and are vital to guarantee an effective and timely emergency response. In particular, Supervisory Control and Data Acquisition, SCADA, are sophisticated communications systems that take measurements and collect data along the network and transmit them to centralized control stations. This enables a quick reaction to equipment malfunctions, leaks, or any other unusual activity along the pipeline.

In-line SCADA hardware includes a variety of components, including:

- Instrumentation.
- Power Supply (normal, backup).
- Communication components (normal, backup).
- Weather enclosures (electrical cabinets and vaults).

SCADA system components in water transmission systems are the following.

- *Instruments attached to the pipeline* may include flow and pressure devices that are sometimes installed in a venture section of pipeline.
- *Instruments attached to a canal* may include various types of float instruments, which are used to assess the water level in the canal.
- *Remote Terminal Units (RTUs) and Programmable Logic Controllers (PLCs)* are most commonly solid state devices. An RTU device picks up the analogue signals from one or more channels of SCADA system devices at one location. The RTU converts these signals into a suitable format for transmission to a central SCADA computer, often at a location remote from the devices. A PLC can control when pumps are turned on or off, based on real time data or pre-programmed logic.
- Most water systems have used *manual recorders* to track pressures, flows and gradient information. These recorders are still in use in many water systems. The recorders sometimes report on the same information as the automated SCADA system, often using the same instruments. Also, since the installation of automated SCADA system hardware is often relegated to a few locations in the water system, the manual recorder may be the only recording device at a location.
- *SCADA Cabinet* is a metal enclosure that is mounted to a floor or bolted to a wall.
Most SCADA systems include battery backups.

Communication Links. The remote SCADA system is connected in some manner to the central location SCADA computer system. The most common links are radio, leased landlines and, to a lesser extent, microwaves; the use of public switched landlines is rare.

Canal gate structures.

1.3 WASTE-WATER NETWORK COMPONENTS

WWN01 Waste-water treatment plant
Complex facilities, which include a number of buildings and underground or on ground reinforced concrete tank and basins. Conventional waste-water treatments consist of preliminary processes, primary settling and secondary biological aeration. Waste-Water Treatment Plants can be categorized by their size (small, medium or large) and by the anchorage (or not) of their subcomponents and backup power. The subcomponents are: Electric Power; Chlorination equipment; Sediment flocculation; Chemical Tanks; Electric equipment; Elevated pipe.

WWN02 Pumping Station
Lift or pumping stations serve to raise sewage over topographical rises or to boost the disposals. They can be categorized according to their size (small or medium/large) and by the anchorage (or not) of their subcomponents and backup power. The following subcomponents may be considered in a pumping station: Electric Power; Vertical/Horizontal Pump; Building; Equipment.

WWN03 Pipelines
Waste-water pipes are usually free flow conduits. Their typology is similar to WSS05.

WWN04 Tunnels (same as WSS06)
2 Systemic vulnerability methodology

The vulnerability assessment of water supply network can be measured generally in four levels (Kakderi et al 2011):

- **Level I (Vulnerability Analysis):** The scope is to estimate the percentage of the physical damages in a specific region based on the vulnerability analysis of water components. The latest can be estimated through appropriate fragility curves or/and Monte-Carlo technique.

- **Level II (Connectivity Analysis):** A vulnerability analysis is essential, as a first step, in order to estimate the physically damaged components (pipes, nodes). In a second stage, the damaged components should be removed from the network. Furthermore, some of the remaining nodes which can be completely isolated from all supply nodes must be removed from the original network. In a third stage, a connectivity analysis may be performed (simplified- Level IIa or advanced- Level IIb).

- **Level III (Flow Analysis):** Firstly, water head, flow rate and amount of leakage at each demand node are calculated under intact (pre-earthquake) conditions as well as the quantity of flow and head loss in each pipe. After the evaluation of the physical vulnerability of the pipes (break, leak), a flow analysis is performed involving the newly formed network. It is assumed that, when a pipe is broken, a shutdown device will be automatically activated at the starting and terminating nodes of the pipe so that the water leakage is prevented. It is also postulated that capabilities of the supply nodes are not reduced by seismic damages.

- **Level IV (Serviceability Analysis):** Vulnerability estimation of water system components beside with a flow analysis is repeated for different seismic intensities using Monte-Carlo simulations. When the task is completed, average values of the flow rate and water pressure are calculated at each node together with their ratio to the corresponding parameters under intact condition. The above procedure comprises a full serviceability analysis (Level IVb). Moreover, a simplified serviceability analysis (Level IVa) can be accomplished connecting the pipeline break rate with a simple Serviceability Index.

The vulnerability assessment of waste-water supply network can be measured generally in three levels (ALA 2004):

- **Level I (Simplified Assessment):** It can be a deterministic one, where the result is calculated directly (no uncertainty taken into account), using scenario events without using the probability of the event in the calculations. A normal probabilistic risk assessment is also possible, using approximations (e.g., high, medium, and low) for the three risk components (hazard, vulnerability, consequence).

- **Level II (Intermediate Assessment):** It is a probabilistic risk assessment using a mean or median value for each of the three risk parameters, with minimal consideration of the variability of each term.

- **Level III (Advanced Assessment):** It is again a probabilistic risk assessment incorporating the variability of one or more of the risk parameters to capture their randomness and uncertainty.
2.1 SYSTEM COMPONENTS VULNERABILITY

Within the seismic vulnerability analysis of a water/waste-water system, water sources, water/waste-water treatment plants, pumping stations, water storage tanks, canals, pipelines and tunnels are considered vulnerable components. Fragility functions for each of these components are provided in the deliverable D3.5 “Fragility functions for water and waste-water systems” (Alexoudi et al, 2010).

2.2 CONNECTIVITY ANALYSIS

2.2.1 Functional modelling

Water and waste-water systems are networks that can be modeled as a graph composed by the set of nodes connected by edge links with each other. The way these connections are formed dictates how the vulnerability of each element influences the vulnerability of the network as a whole.

Let \( V \) be a finite set, and denote by \( E(V) = \{\{u, v\} \mid u, v \in V, u \neq v\} \) the 2-sets of \( V \), i.e., subsets of two distinct elements.

A pair \( G = (V, E) \) with \( E \subseteq E(V) \) is called a graph (on \( V \)). The elements of \( V \) are the vertices of \( G \), and those of \( E \) the edges of \( G \). The vertex set of a graph \( G \) is denoted by \( V_G \) and its edge set by \( E_G \). Therefore \( G = (V_G, E_G) \). In literature, graphs are also called simple graphs; vertices are called nodes or points; edges are called lines or links.

For a graph \( G \), we denote \( \nu_G = |V_G| \) and \( \varepsilon_G = |E_G| \). The number \( n_G \) of the vertices is called the order of \( G \), and \( \varepsilon_G \) is the size of \( G \). For an edge \( e = uv \in G \), the vertices \( u \) and \( v \) are its ends.

Vertices \( u \) and \( v \) are adjacent or neighbours, if \( uv \in E \). Two edges \( e_1 = uv \) and \( e_2 = uw \) having a common end, are adjacent with each other. A graph \( G \) can be represented as a plane figure by drawing a line (or a curve) between the points \( u \) and \( v \) (representing vertices) if \( e = uv \) is an edge of \( G \).

Graphs can be generalized by allowing loops \( vv \) and parallel (or multiple) edges between vertices to obtain a multigraph \( G = (V, E, \psi) \), where \( E = \{e_1, e_2, \ldots, e_m\} \) is a set (of symbols), and \( \psi: E \to E(V) \cup \{vv \mid v \in V\} \) is a function that attaches an unordered pair of vertices to each \( e \in E \): \( \psi(e) = uv \). These are loop graphs, opposed to tree graphs; pipeline systems can be of tree or loop type, with the first ones being easier to be calculated. This is due to the looped nature, flow and direction of each pipe which cannot be easily calculated. Usually distribution systems are not tree type, having the task of reaching as close as possible to the end user.

Graphs can be divided into directed graphs and undirected graphs. In directed graphs or digraphs \( D = (V, E) \), where the edges have a direction, that is, the edges are ordered: \( E \subseteq V \times V \). The directed graphs have representations, where the edges are drawn as arrows. A digraph can contain edges of opposite directions.

A directed graph is called strongly connected if there is a path from each vertex in the graph to every other vertex. In particular, this means paths in each direction. The strongly connected components of a directed graph \( G \) are its maximal strongly connected subgraphs. If each strongly connected component is contracted to a single vertex, the resulting graph is a directed acyclic graph, the condensation of \( G \). A directed graph is acyclic if and only if it has no
(nontrivial) strongly connected subgraphs (because a cycle is strongly connected, and every strongly connected graph contains at least one cycle). For the case of water and waste-water systems, they are strongly connected if there is flow in one direction between every two positions. The networks are weakly connected if there is flow in both directions between every two positions. The network is disconnected if there is no possible way for the water/waste-water to flow from one point to another.

Different graph theory algorithms and numerical methods exist, each of them solve different problems. Dijkstra’s algorithm solves the shortest path problem for a directed graph with non-negative edge weights. For example, this algorithm can be used to find the shortest route between two pumping stations. The Depth First Search algorithm instead is used to determine which nodes are reachable from a given node. More details on graph theory algorithms can be found in Christofides (1975).

Graph theory is very useful to represent the network computation of any topology and to check the connectivity of the water/waste-water network systems.

### 2.2.2 Connectivity evaluation

In the seismic vulnerability assessment the general aim of a connectivity analysis is to determine if a demand node is accessible from at least one supply node after the occurrence of a seismic event. It is important to note that if only the distribution part of the network is of concern, node functionality changes. In particular considering only the distribution network, storage tanks become source nodes. Within the implemented Object-Oriented (OO) software (see Section 3), the analysis is focused on the Infrastructure at the urban/regional scale and, hence, only the transmission system is modeled in the water supply network vulnerability analysis. For this reason, water sources (WSS01 components), eventually served by pumping stations, are considered as constant head source nodes, whereas storage tanks located inside cities are the demand nodes.

### 2.3 FLOW ANALYSIS

The functioning of a WSS is described analytically by a set of $N+L$ nonlinear equations in $N+L$ unknowns, written in matrix form as (Franchin et al. 2011):

\[
\begin{bmatrix}
A_N^T \mathbf{q} - \mathbf{Q}(\mathbf{h}_N) \\
\mathbf{R} \mathbf{q} + (A_N \mathbf{h}_N + A_S \mathbf{h}_S)
\end{bmatrix} = 0
\]

(0.1)

where $N$, $L$, and $S$ are the number of internal (non-source) nodes, the number of links and the number of water sources, respectively. The first $N$ equations are balance equations and express flow balance at the internal nodes (sum of incoming and outgoing flows equal to zero or the end-user demands $\mathbf{Q}(\mathbf{h}_N)$ in end-user nodes), while the second $L$ equations express resistance in the links.

The $L \times N$ and $L \times S$ matrices $A_N$ and $A_S$ are sub-matrices of the $L \times (N+S)$ matrix which contains 0, 1 and -1 terms as a function of the network connectivity. The $N \times 1$ and $S \times 1$ vectors $\mathbf{h}_N$ and $\mathbf{h}_S$ are the corresponding partition of the $(N+S) \times 1$ vector $\mathbf{h}$ collecting the $N$ unknown heads in the internal nodes and the $S$ known heads in the water-source nodes. The $L \times 1$ vector $\mathbf{q}$ collects the
unknown flows in the \( L \) links and \( R \) is the \( L \times L \) diagonal matrix of resistances, with terms \( r_i = u_i L_i \), where \( u_i = \beta D^{-5} \) (according to Darcy’s law) and \( L_i \) the i-th link length.

It can be observed that in the above set of equations the end-user demands \( Q(h_N) \) are written as functions of the unknown heads in the internal nodes. The solution of the system in this form is called “head-driven”, and is what should be used in the perturbed seismic conditions where satisfaction of prescribed demands is not guaranteed. It is customary in the analysis of WSS for the purpose of design to treat the end-user demands \( Q \) as fixed boundary conditions (the system must be proportioned in order to satisfy them). The solution of the system with \( Q \) independent of \( h_N \) is called “demand-driven”.

The set of nonlinear equations holds in so-called stationary conditions, i.e. it assumes constant end-user demands. This is a simplification, which is valid as long as the boundary conditions vary smoothly with time, in which case one speaks of quasi-stationary conditions. In seismic conditions this is not the case but the abrupt variation due to ruptures and leakages is soon replaced by a new stationary state.

Solution of the above set of equations by a numerical algorithm allows verification of the serviceability levels in each end-user node. The performance indicators to express satisfaction of performance requirements are reported by Kakderi et al (2011). In general, however, what is required is that heads are always positive and larger than minima within accepted ranges depending on the typology of the end-users. Heads should never fall below 5m above the highest tap in the building which is “hydraulically” farthest away from the water sources, nor should they be more than 70m above the lowest floors taps in order to avoid excessive pressure and damage to equipment. Further requirements and range modifications can follow from fire fighting needs when the systems are not separated.
2.4 INTER-DEPENDENCIES

The interdependencies between water and waste-water networks and the other systems are described in Table 2.1. They are distinguished in physical (direct) and informational, geographic, restoration, substitute (indirect). Furthermore, they are classified as crucial, important and secondary. Within SYNER-G it was decided to study only the direct/crucial interactions.

### Table 2.1 Interdependencies between WSS, WWN and other networks as identified in SYNER-G

| Impacts                        | BDG | EPN | WSS       | WWN       | GAS | OIL | RDN | HBR | HCS | FFS | SHM | HIM |
|-------------------------------|-----|-----|-----------|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Buildings                     | BDG |     | 2-Geo,    | 3-Geo,    |     |     |     |     |     |     |     |     |     |
| Electric power network        | EPN |     | 1-Phy     | 1-Phy     |     |     |     |     |     |     |     |     |     |
| Potable water network         | WSS |     | 1-Phy,    | 3-Phy,    |     |     |     |     |     |     |     |     |     |
| Waste-water network           | WWN |     | 2-Phy     | 3-Phy     |     |     |     |     |     |     |     |     |     |
| Gas network                   | GAS |     |           |           |     |     |     |     |     |     |     |     |     |
| Oil network                   | OIL |     |           |           |     |     |     |     |     |     |     |     |     |
| Road network                  | RDN |     | 3-Geo,    | 3-Geo,    | 3-Geo,| 3-Geo,|     |     |     |     |     |     |     |
| Harbour                       | HBR |     | 3-Res     | 3-Res     |     |     |     |     |     |     |     |     |     |
| Health-care system            | HCS |     |           |           |     |     |     |     |     |     |     |     |     |
| Fire-fighting system          | FFS |     | 2-Sub     |           |     |     |     |     |     |     |     |     |     |
| Shelter model                 | SHM |     | 3-Phy     | 3-Phy     |     |     |     |     |     |     |     |     |     |
| Health impact model           | HIM |     |           |           |     |     |     |     |     |     |     |     |     |
Priorities definitions:
1-Crucial dependencies
2-Important dependencies
3-Optional/secondary dependencies

Types of interactions:
Direct:
Phy: Physical, functional interdependency - functional damage propagation

Indirect:
Inf: Cyber, informational interdependency
Geo: Collocation, geographic, space interdependency - physical damage propagation
Res: Restoration - recovery interdependency
Sub: Substitute interdependency
3 Software implementation

Following the taxonomy presented in the deliverable D2.1 “General methodology for systemic seismic vulnerability assessment” (Franchin et al. 2011), water/waste-water systems are subclasses of the Network class. The modeling of physical behavior in respect to the general methodology and prototype software presented in the deliverable D2.1 consists of the identification of attributes and methods to implement for the vulnerability assessment. This section provides an overview on the modeling of physical behavior of the water distribution system.

3.1 WATER DISTRIBUTION SYSTEM CLASS

3.1.1 The WSS class

The water supply system is made up of nodes and links connecting them. As a consequence, the WSS class is the composition of WSSLink and WSSNode abstract classes, of which the first is the generalization of the Pipe and Tunnel classes, while the second is the generalization of the DemandNode, WaterSource and PumpingStation classes. In particular, the WaterSource abstract class is the generalization of the VariableHeadWaterSource and ConstantHeadWaterSource classes. The WSS is dependent upon the built area for what concerns the estimation of the water demand. Another important interdependence considered within SYNER-G is between the WSS and EPN, in particular about the electric power supply to the pumping stations. If a pump serving a source node is not fed by the reference EPN node with power at a sufficient voltage level, then the pump itself is considered out of service and the WSS node loses its source function. Figure 3.1 illustrates the class diagrams and the interaction of the two networks.

![Fig. 3.1 Class diagram for the WSS and EPN classes](image-url)
The following is the list of properties of the WSS class, with the names following the naming convention adopted for variables in developing the prototype software, whereby multi-word names have no blank spaces in between words and the latter are separated by capitalizing the initial letter of each word. The list is split into four parts:

List of pointers

- **parent**: this is a pointer to the parent object which, in this case, is the Infrastructure (the object from the Infrastructure class)
- **pipe**: pointers to all the pipes in the system, objects from the Pipe class
- **demand**: pointers to all end-user nodes, objects from the DemandNode class
- **source**: pointers to all sources in the system, in general objects from the ConstantHeadWaterTank and VariableHeadWaterSource classes (at the present stage, though, the prototype software includes only the ConstantHeadWaterTank class)
- **pump**: pointers to objects from the PumpingStation class

Water supply system global properties

- **nEdges**: number of links or edges in the WSS
- **nNodes**: number of nodes in the WSS
- **edgeDiameterNumber**: number of diameter sizes present in the WSS
- **edges**: connectivity matrix of the WSS listing the start and end nodes of each link
- **refEPNnode**: node(s) of the EPN which feeds power to the pumping station(s)
- **sourceHead**: water head at the source nodes
- **endUserDemand**: water flows at demand nodes
- **hydricEquipment**: water daily equipment of the region of interest
- **vulnSites**: list of vulnerable sites of the WSS, containing their location and IM type(s)
- **adjacencyMatrix**
- **incidenceMatrix**
- **incidenceList**
- **dead Ends**: list of network dead ends
- **articPTS**: list of network articulation points
- **bridges**: list of network bridges

Link and node characteristics

- **edgeVs30**: Vs30 value at the links centroid
- **edgeType**: typology (pipe or tunnel) of links
- **edgeDiameter**
- **edgeRoughness**
- **edgeDepth**: laying depth of links
Software implementation

- **edgeIsVulnerable**: flag indicating if the generic link is considered vulnerable or not
- **edgeIMType**
- **edgeCentroidPosition**
- **edgeMaterial**
- **edgeLength**
- **edgeSiteClass**: site class at the edge centroid site according to the amplification method to be used
- **edgeDepth2GW**: depth of the groundwater at the edge centroid site
- **edgeLiqSusClass**: liquefaction susceptibility of the edge centroid site
- **edgeLandSusClass**: landsliding susceptibility of the edge centroid site
- **edgeYieldAcc**: yielding or critical acceleration for landsliding at the edge centroid site
- **nodePosition**
- **nodeAltitude**
- **nodeMinimalHead**: minimal head required at nodes for delivery of the assigned demand water flow; this property is a function of the average building elevation in the region of interest
- **nodeDepth**: laying depth of nodes
- **nodeType**: typology (demand, source or pumping station) of nodes
- **nodeVs30**
- **nodeIsVulnerable**
- **nodeIMType**
- **nodeSiteClass**: site class at the node site according to the amplification method to be used

*Properties that record the state of the WSS for each event*

- **states**: \( n_E \times 1 \) collection of properties that describe the current state for each of the \( n_E \) events
  - **AHR**: Average Head Ratio, first system-level performance indicator (Kakderi et al 2011)
  - **SSI**: System Serviceability Index, second system-level performance indicator (Kakderi et al 2011)
  - **covAHR**: coefficient of variation of AHR
  - **covSSI**: coefficient of variation of SSI
  - **covTot**: maximum value among covAHR and covSSI; this value is monitored during simulation, so to stop the simulation itself in case its threshold is reached
  - **mean_AHR**: moving average of AHR over the simulation, until the current run
  - **mean_SSS**: moving average of SSI over the simulation, until the current run
Software implementation

- **mean_HR**: moving average of HR over the simulation, until the current run
- **mean_DCI**: moving average of DCI over the simulation, until the current run
- **mean_UBI**: moving average of UBI over the simulation, until the current run
- **std_AHR**: moving standard deviation of AHR over the simulation, until the current run
- **std_SSI**: moving standard deviation of SSI over the simulation, until the current run

*Properties that assess the global performance of the WSS at the end of simulation*

- **MAF**: Mean Annual Frequency of exceedance values for the considered system-level PIs

The following is the list of the main methods of the WSS class (some of these are briefly explained):

- anySDFS
- buildSymAdjMatrix
- buildSymIncList
- computeCovMean
- computeCovMeanIS
- computeDemand
- computeFlow
- computePerformanceIndicator
- connectedNodes
- detectArticulationPoints
- detectBridges
- discretizeEdges
- edges2Adjacency
- edges2IncidenceList
- edges2IncidenceMatrix
- findDeadEnds
- getListOfLists
- isConnected
- minPath
- retrieveLandSusEdges
- retrieveLiqSusEdges
- retrieveSiteClassEdges
- retrieveSiteClassNodes
- retrieveVs30edges
The `computeFlow` method performs the computation of flows in all pipes and heads in all demand nodes, in both seismic and non-seismic conditions. In the prototype software this method, run after the estimation of pipes damage (leaks and/or breaks) and the eventual updating of the network connectivity, finds the solution of the nonlinear system in Eq. (3.1) by using one the classical derivative algorithms, the Newton-Raphson method.

The `computeDemand` method determines the water flow for all demand nodes in which the flow is set to 0 in the textual input. The computation for the generic demand node is based on the user-specified water daily equipment and the population of its reference cells, if any, i.e. the cells fed by the node itself.

Within the `discretizeEdges` method, all the links with a length greater than a threshold are subdivided into smaller segments, so to allow a more refined computation of links intensity measure(s) and, consequently, damage.

The `updateConnectivity` method, based on the network damage for the generic event, sets to 0 the elements in the adjacency matrix corresponding to broken edges.

### 3.1.2 The WSSLink class and sub-classes

The following is the list of properties of the `WSSLink` abstract class. These properties are common to all subclasses (Pipe and Tunnel) of this class.

- **parent**: this is a pointer to the parent object which is in this case the water supply system (the object from the WSS class)
- **siteClass**
- **connectivity**: start and end node of the link
- **centroid**: link centroid location
- **L**: link length
- **D**: link diameter
- **Roughness**: link roughness
- **Vs30**: Vs30 at link centroid
- **isVulnerable**
- **IMType**
- **material**
- **depth2GW**
- **liqSusClass**
- **landSusClass**
- **yieldAcc**
1. The subclass Pipe has one further property, i.e. **Depth**, that objects of this class do not share with those of class Tunnel.

2. The following is the list of the methods of the **WSSLink** abstract class. These methods must be present in all subclasses (Pipe and Tunnel) of this class, although can have different implementations in the subclasses.
   - isBreakAndLeaksNumber
   - computeLeakageArea
   - plotStateLink

   The **isBreakAndLeaksNumber** method samples a number of damages (leaks/breaks) due to both PGV and PGD, assuming that the damages number along a water link is Poisson distributed. Then, if at least one damage is a break, the edge is considered broken and removed from the network (a check on isolated nodes will follow), otherwise all the damages are considered as leaks in the next flow computation.

   The **computeLeakageArea** method computes the total outflow area, e.g. assuming an area for each leak along the link equal to 3% of the whole link section.

3. **The WSSnode class and sub-classes**

   The following is the list of properties of the **WSSNode** abstract class. These properties are common to all subclasses (DemandNode, **WaterSource** and **PumpingStation**) of this class.
   - parent: this is a pointer to the parent object which is in this case the water supply system (the object from the WSS class)
   - position: node location
   - altitude: node altitude
   - type: typology (demand, source or pumping station) of the node
   - Vs30: Vs30 at node
   - isVulnerable
   - IMType
Software implementation

- **states**: \( nE \times 1 \) collection of properties that describe the current state for each of the \( nE \) events
  - **demandFlow**: demand water flow at the node
  - **head**: water head at the node
  - **outFlow**: water flow outgoing from the node, simulating half the flows outgoing from all links converging in the node
  - **HR**: Head Ratio, component-level performance indicator

The subclass DemandNode has two further properties, i.e. **minimalHead** and **referenceCells**, that objects of this subclass do not share with those of the other subclasses. Only the subclass *Water-Source* has one further property, i.e. **head**. Only the subclass PumpingStation has two further properties, i.e. **refSource** and **refEPNStation**, indicating respectively the source node served by the pumping station and the EPN node which feeds power to the pumping station. The *WSSNode* abstract class does not have any methods. The concrete subclasses (DemandNode, *Water-Source* and PumpingStation) have only the object constructor method.
References

ALA (2004). Wastewater System Performance Assessment Guideline, Part I and II. FEMA and NIBS.


