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SEISMIC ASSESSMENT TO GAS AND OIL LIFELINES

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SUMMARY

The main purpose of this study is to assess and evaluate the seismic vulnerability of gas and oil networks, whose results can be used to predict probable damages and system performance in future earthquakes. The vulnerable elements of these networks are defined and their seismic vulnerability evaluated. The methodology used to assess the observed damages is based in the proposal of HAZUS99 [1], with the addition of various adjustments. The seismic assessment is defined knowing the components of the systems, their classification and the expected ground movement. The methodology is applied to parts of the main network of natural gas as oil systems. This procedure enables the definition of the fragility curves for all the components other than the pipelines, i.e. the evaluation of the probabilities associated to each state of damage, as well as the damage functions for the buried pipelines.

INTRODUCTION

The concern on the seismic protection of gas and oil networks, mainly composed by buried pipelines, has been growing in Portugal in the last few years. In particular, in the Lisbon surrounding area, this problem has an increased importance, considering that is a large region that is presenting recently a high demographic growth as well as great concentration of residential and industrial facilities served by the existent gas and oil distribution networks. Besides, Lisbon and the neighboring areas have a potential seismic activity.

The direct and indirect consequences of the occurrence of an earthquake in both referred networks are very important aspects to be considered by the Government entities and agencies of emergency management. Although some regions, depending on their characteristics, are more vulnerable to the occurrence of earthquake, the elaboration of vulnerability studies of gas and oil networks, as well as the definition of emergency plans, should be current practice, to allow the reduction or until the elimination of the risks and damages caused by that natural phenomenon.

The importance of gas and oil networks together with others, such as highways, electricity, water supply, sewage and telecommunications, is that they are directly connected with the social and economical

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activities and practices observed in the areas affected by earthquakes. All of these networks are responsible for the development of the modern societies. In particularly, in what concerns the surrounding area of Lisbon, with an historically seismic activity, everything that allows to predict the probable performance of the networks (in which the gas and oil are included) after the occurrence of a seismic action is a decisive factor for the prevention of risk situations: i) for allowing to define the economical-social activities to undertake after the earthquake and ii) for assuring the appropriate intervention of the government and operational entities responsible for the affected area. This way, it will be possible that the mentioned entities will be prepared and try to foresee the consequences of an earthquake of considerable magnitude.

Based on seismic vulnerability studies it will also be possible to present new proposals that allow to the responsible entities to undertake the necessary modifications in order to improve the seismic performance of lifeline systems. Moreover, the vulnerability studies are also very important for immediate rescue planning procedures in catastrophe situations.

SEISMIC VULNERABILITY OF GAS AND OIL NETWORKS

The evaluation of the seismic vulnerability of all the elements of the gas and oil networks can be made from empiric relationships previously known, based in the damages observed in previous earthquakes. The referred empiric relationships are based on the statistical treatment of the consequences of an earthquake in the structures in subject.

The effects of the seismic action in structures can be considered based on: i) a structural definition (physics) or ii) an operational definition (functional). For the definition of the seismic assessment of these structures, vulnerability functions are used, defined from the analysis of the structural behavior for different levels of seismic intensity, quantified in terms of:

- Peak ground acceleration (PGA);
- Peak ground velocity (PGV);
- Permanent ground deformation (PGD);
- Seismic intensity (MMI).

For buried pipelined (the main components of this type of networks) the PGV is the measure frequently adopted to quantify the dynamic effect of the seismic action (seismic waves propagation), because it was observed in other studies that the stress measured in the soil, and consequently in the pipelines, is directly related with that peak value. In some other situations the seismic intensity scale, as the MMI [1], is adopted. However, as the most relevant damage in gas and oil networks results of the permanent deformations of the soil (liquefaction, lateral spread and active faults) the characterization of the seismic action, for the definition of vulnerability functions, is defined based on the permanent deformations of the soil (PGD).

In this study, the earthquake effects in the components other than the buried pipeline of the gas and oil networks are characterized in terms of the affected operational capacity, immediately after the seismic action (direct damages).

DEFINITION OF THE MAIN COMPONENTS OF THE GAS AND OIL NETWORKS

As previously referred, the main purpose of this research is the assessment and the evaluation the seismic vulnerability of gas and oil networks, which can be used to estimate expected damage and system performance in future earthquakes. In this work, it is studied the principal line of the existing natural gas networks in Lisbon's area (called TRANSGÁS), as well as the oil network (CLC). Figure 1 shows in green the TRANSGÁS line and in red the main part of the CLC network. The gas networks are constituted of buried pipelines (in some particular cases not buried), centers of ruling and compressor stations. Relatively to the oil networks its components are buried pipelines, refineries, pumping plants and tank farms.

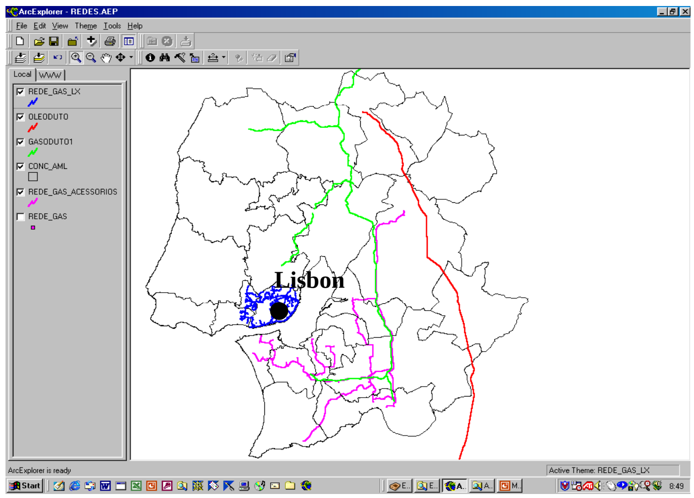
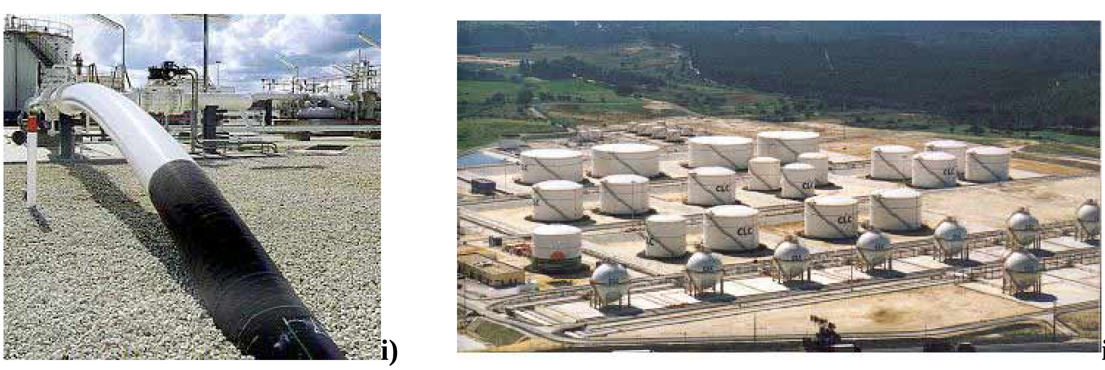


Figure 1 – Gas and oil networks

In the Portuguese gas networks the only existing components, besides the ruling centers and the buried pipelines (with a diameter of 711.2 mm), are the compression stations which function is to reduce and measure the flow inside the pipelines (PRP and PRM). The compression stations are similar to the pumping plants of the oil networks that maintain the fluency of the gas in the pipelines that cross great extensions of a certain area or country. The referred compression stations include centrifugal and reciprocal compressors, although any distinction is made among the developed analyses for these two types of elements of the systems of gas. It may also be distinguished compression stations with or without anchored subcomponents that correspond to situations for which special seismic design was, or not, considered. The compression stations are vulnerable to the PGA and mainly to PGD, if they are located in areas with great probability of occurrence liquefaction or land sliding or where is known the existence of active faults.

For the Portuguese oil network the other components, besides the buried pipeline (Figure 2-i), are the command center, equivalent to the centers of ruling of the gas networks, the refinery (only one located in Sines), the pumping plants and the tank farm in Aveiras, nearby Lisbon (Figure 2-ii).



i) ii)

Figure 2 –Oil network: i) Pipeline; ii) Tank farm

The oil buried pipeline has a diameter of 406.4 mm and is made of steel API 5L X65, a ductile material.

The refineries are important parts of a system of oil provisioning, being used in the treatment of the crude before its use. The methodology proposed in HAZUS99 [1] considers two sizes of refineries: small and medium/large. The small refineries, that present maximum capacity of 100000 gallons/day, are constituted by diverse elements: metallic tanks, piles of barrels, other electrical and mechanical equipments and, still, not buried pipelines. The referred piles are essentially very high cylindrical chimneys. The medium/large refineries, with capacity larger than 100000 gallons/day, are obtained by addition of more redundancy than the small refineries (for instance: duplication of the tanks, the piles and the not buried pipelines).

The pumping plants exist fundamentally to maintain the fluency of the fuels in the buried pipelines. The fluency is obtained by the use of bombs, in number of two or even more. The types of bombs used can be centrifugal or alternate. However any distinction is made between these two types of bombs in the analysis of the Portuguese oil network studied. The pumping plants are classified as presenting or not anchored subcomponents.

Finally, in the oil networks, there are another components to be considered: the tank farms. These components are responsible for the storage of the fuels and include tanks, pipelines and electrical components. As the pumping plants they may be classified as presenting, or not, anchored subcomponents.

The refineries, pumping plants and tank farms are vulnerable to PGA or PGD values, when located in areas that present high liquefaction potential or in areas in that is verified a predisposition for the occurrence of land sliding or where is known the existence of active faults. Knowing that the tank farms are the components that determine the type of damages in the storage compounds of the oil networks, during this study the resulting damages of the occurrence of a certain seismic action in the oil networks is referred to the tanks.

The buried pipelines, for gas and oil networks, present important seismic vulnerability to high PGV values and, mainly, to PGD values. As such, it can be concluded that the resulting damages of the occurrence of a certain seismic scenario in gas and oil networks are associates to three characteristic parameters of the of the soil's movement: PGA (for the components other than the buried pipelines), PGV (for the buried pipelines) and PGD (for all type of components).

EVALUATION OF THE DAMAGES IN THE NETWORKS COMPONENTS

In the following section it will be defined briefly the methodology proposed in HAZUS99 [1] with the addition of several adjustments for the components of the gas and oil networks.

For the damage quantification of all the components of the networks is necessary, firstly, to identify its origin. In fact, the damage in all these components of the networks can be due:

- To the dynamic action imposed by the movement of the soil (DIN);
- To the rupture of the soil:
  - liquefaction (LIQ);
  - lansliding (DESL);
  - movement of a geological active fault (FAL).

Known the origin of damages, their assessment in the different components of the studied networks is defined from fragility curves, for the not buried components, or from damage functions, for the buried pipelines.

The fragility curves present lognormal distributions and they show the probability of being reached or exceeded different damage levels (d_{si}) for a certain type of seismic scenario and movement of the soil. It is possible to define a total of five damage levels (from d_{s1} to d_{s5}) for all the not buried components of these gas and oil transport and distribution systems:

- No damage (d_{s1})
- Slight/minor damage (d_{s2})
- Moderate damage (d_{s3})
- Extensive damage (d_{s4})
- Complete damage (d_{s5})

On the other hand, the damage functions define the number of repairs for buried pipelines, based on the number of repairs for unit of length (repairs/km), so called repairs rate.

The fragility curves, for all the components other than the buried pipelines, are defined from the average values of PGA and PGD (this last one in the case of occurring the rupture of the soil) and for the correspondent dispersion factor. For the buried pipelines the damage functions are defined by means of the values of PGV and PGD.

For all the components it was performed a correction to the values assumed for the quantification of the seismic actions [2] because the values proposal in HAZUS99 [1] correspond to the reality of the United States. In fact, in United States the maximum value adopted for the seismic action is 0.4g while for Portugal the limit is defined for 0.3g. As the correspondence between the values is about 2/3 it was suggested [2] to correct the medium values defined by HAZUS99 and use the corrected value in the application of the methodology to the Portuguese gas and oil networks.

Fragility curves for the components other than the buried pipelines

In this study, for the not buried components is necessary considering each one of the suitable soil effects previously mentioned, to identify the entrance variables and the correct methodology to adopt for the determination of the probabilities associated to each level of damages and for the definition of the fragility curves. It is necessary to separate the dynamic effect and the rupture of the soil.

From the mentioned phenomena which caused permanent ground deformations (PGD) the one induced by liquefaction are considered as the main cause of damage in buried pipelines and in all the others components, having liquefaction precisely been adopted in this work as cause of ground rupture and as the origin of the high values of ground deformations considered.

Probabilities of damages associated to the dynamic effect - $P\,[Ds \geq ds_i]_{DIN}$

The probabilities of damage due to the dynamic effect of the seismic action and for the components other than the buried pipelines are evaluated according the fragility curves presented in equation 1. Their definition is function of the peak ground deformation (PGA) and of the classification of the components in study.

These fragility functions give the probability of reaching or exceeding different damage states (ds_i) for a given level of ground motion (PGA). Each of these fragility curves is defined by a median value of the ground motion (X_i), or ground failure, and an associated dispersion factor (β_i). Thus, the probability of being in or exceeding a damage state ($P_a[D_s \geq ds_i]$), for a given PGA value, is modeled according to equation 1, where ϕ is the standard normal cumulative distribution function. Similar expression is defined in the case of ground failure (see equations 2 and 3).

In the gas networks the components are compression stations and, as referred, for the fragility curves definition it is important to classify these components; in this network all the components are anchored. Based on this classification, HAZUS99 defines, for each damage state, values for the median value of ground motion X_i (corrected for the Portuguese networks) and for an associated dispersion factor β_i. With these values defined, associates to each state of damage, the probabilities of damage correspondents are then evaluated according equation 1.

$$P[Ds \geq ds_i]_{DIN} = \Phi\left(\frac{\ln[PGA] - \ln[X_i^c]}{\beta_i}\right) \qquad i = 2,3,4 \text{ e } 5 \qquad (1)$$

Φ - standard normal cumulative distribution function.

Regarding the oil networks the characterization of the refinery is defined based in the existence, or not, of anchored components and in its capacity (small or medium/large). The Refinery of Sines, the only refinery existent in the studied network, corresponds to a medium/large refinery with anchored components. The pumping plant existent in Sines has anchored components, according with the definition adopted. For the tank farms, all located in Aveiras, the existence of seismic design in their components was verified, then all these tanks are classified as anchored components.

Probabilities of damages associated to the rupture of the soil (liquefaction) - $P[Ds \geq d_{si}]_{LIQ}$
The liquefaction of the soil is related with two different phenomena: lateral spread and settlement. So it is necessary, for each damage state d_{si}, to evaluate the probabilities of occurrence of each one of these phenomena. For the evaluation of the global probabilities of damage for each component it has to be considered the probabilities associated with the occurrence of the most probable phenomena (lateral spread or settlement). The entrance variables are the ones related with seismic action and the classification of the component. To identify the seismic action it should be introduced the value of the probability of happening the liquefaction of the soil liquefaction (p_{LIQ}) and the values associated to the existence of permanent lateral spread (PGD_{LAT}) or settlement (PGD_{ASS}) due to the liquefaction.

To classify the components the procedure is similar to the one referred for the dynamic effect of the seismic action. Based on the classification of the component, the medium values (X_{RFi}) and of the standard deviation of variable lnx (β_{Rfi}) associates to each damage state (and corresponding to the rupture of the foundation of the components - RF) are proposed. The probabilities of damage are defined according to equations 2 and 3, due to the lateral spread and settlement, respectively.

i) Damages due to lateral spread

$$P[Ds \geq ds_i]_{LAT} = \Phi\left(\frac{\ln[PGD_{LAT}] - \ln[X_{RF\,i}^{\,c}]}{\beta_{RF\,i}}\right) p_{LIQ} \qquad i = 2,3,4 \text{ e } 5 \qquad (2)$$

ii) Damages due to settlement

$$P[Ds \geq ds_i]_{ASS} = \Phi\left(\frac{\ln[PGD_{ASS}] - \ln[X_{RF_i}{}^{c}]}{\beta_{RF_i}}\right) p_{LIQ} \qquad i = 2,3,4 \text{ e } 5 \tag{3}$$

Finally, the probability of damage associated to the liquefaction of the soil is the maximum (MAX) value obtained, that means:

$$P\,[Ds \geq ds_i]_{LIQ} = MAX\,\{P\,[Ds \geq ds_i]_{LAT};\; P\,[Ds \geq ds_i]_{ASS}\} \tag{4}$$

Damage functions for buried pipelines

For to the buried pipelines the damages caused by seismic waves propagation (dynamic effect of the seismic action) and by the permanent ground deformations (rupture of the soil) are also studied separately.

Damage functions due to dynamic effect of the seismic action

The damage algorithm for the studied gas and oil ductile buried pipelines due to the dynamic effect is presented in equation 5, in terms of repairs per length (RR – repairs/km). The expression is based on the one proposed in HAZUS99, which is a function of the PGV and does not include the influence of the diameter of the pipeline. To consider the influence of different diameters, the factor K_ϕ was proposed [3]. Equation 5 is applied only for ductile structures and is valid for PGV values in centimeters per second (cm/s).

$$RR_{PGV}[\text{repairs/km}] = 0.00003\, K_\phi PGV^{\,2.25} \tag{5}$$

Damage functions due to ground failure

The assessment of damage for ductile buried pipelines due to ground failure is defined by means equation 6. The repairs rate (RR) is a function of permanent ground deformations (PGD in cm) – due to liquefaction, landslide or superficial rupture of geological fault – and a function of the ground failure occurrence probability (PROB). The probability value is defined according the type of the rupture of the soil: liquefaction - $PROB_{LIQ}$, land sliding - $PROB_{LANDS}$ or geological fault - $PROB_{FAL}$). The expected value of the permanent displacement can be due to the liquefaction phenomenon (PGD_{LAT} or PGD_{ASS}), land sliding (PGD_{LANDS}) or due to the occurrence of movements in a geological fault (PGD_{FAL}).

$$RR_{PGD}[\text{repairs/km}] = 0.18\, PROB\; PGD^{\,0.56} \tag{6}$$

Breaks rate definition

Regarding HAZUS 99 methodology it is important to remember that the breaks rate are assumed to be 20% of the total repairs rate, when damage is caused by seismic wave propagation.

In this study, the breaks rate are then assumed to be 20% of the total repairs rate and the flows rate the remains 80%, when damage is caused by seismic wave propagation. While the damages due to the rupture of the soil correspond to 20% of flows and 80% of breaks. Thus, if it does not happen any phenomena associated to the rupture of the soil, the number of ruptures in the buried pipeline (RUPT – ruptures/km) will be obtained according to equation 7. In the other hand, if the rupture of soil occurs the ruptures rate are evaluated from equation 8.

$$RUPT\,[\text{ruptures/km}] = 0.000006\, K_\phi\, PGV^{\,2.25} \tag{7}$$

$$\text{RUPT [ruptures/km]} = 0.000006\, K_{\phi}\, \text{PGV}^{2.25} + 0.144\, \text{PROB PGD}^{0.56} \quad (8)$$

APPLICATION OF THE METHODOLOGY

Buried pipelines

Despite the analytical studies performed by Falcão [3] it is presented in this paper damage functions of the TRANSGÁS and CLC buried pipelines based on the HAZUS99 methodology. The factor that allows to include the influence of the pipeline's diameter is 0.5 for the TRANSGÁS pipelines and 0.8 for the CLC's [2], and was based on the Isoyama studies [4].

For a better comparison between the damages in the buried pipelines and in all the other components it is necessary to consider the same measurement value of the seismic action. Thus it is necessary to change the PGV input into PGA values and establish a connection between them. In the conversion it was used the relation proposed by Krinitzky and Chang [5] for smooth soils, that enables to change PGV value into MMI values – equation 9. Afterwards it was used the relation proposed in HAZUS99 that allows to obtain PGA values based on MMI values – Table 1:

$$\text{MMI} = \frac{\log \text{PGV} + 0.224}{0.179} \quad (9)$$

PGV in cm/s

Table 1: PGA function of MMI[2]

MMI	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
PGA	0.12	0.21	0.36	0.53	0.71	0.86	1.15

Figure 3 presents, in a logarithm scale, the values obtained for the repairs rate in TRANSGÁS and CLC buried pipelines, function of PGA (i) and PGD (ii).

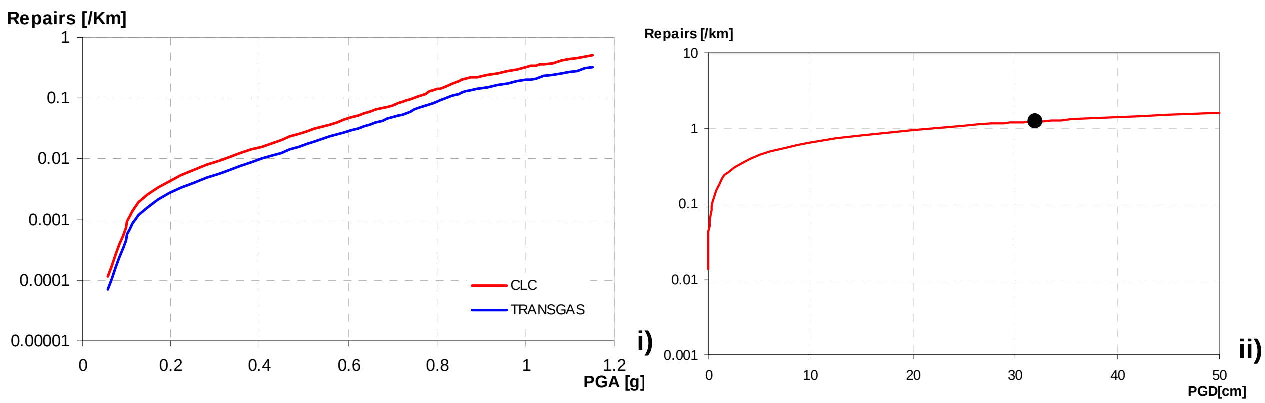


Figure 3 - Repairs in the TRANSGÁS and CLC buried pipelines (i) PGA and (ii) PGD

The ruptures rate relationships (equation 7 and second part of the equation 8) are defined graphically in Figure 4. The two effects are showed separately, but when the soil's rupture occurs the ruptures rate is the sum of the two effects, as previously referred.

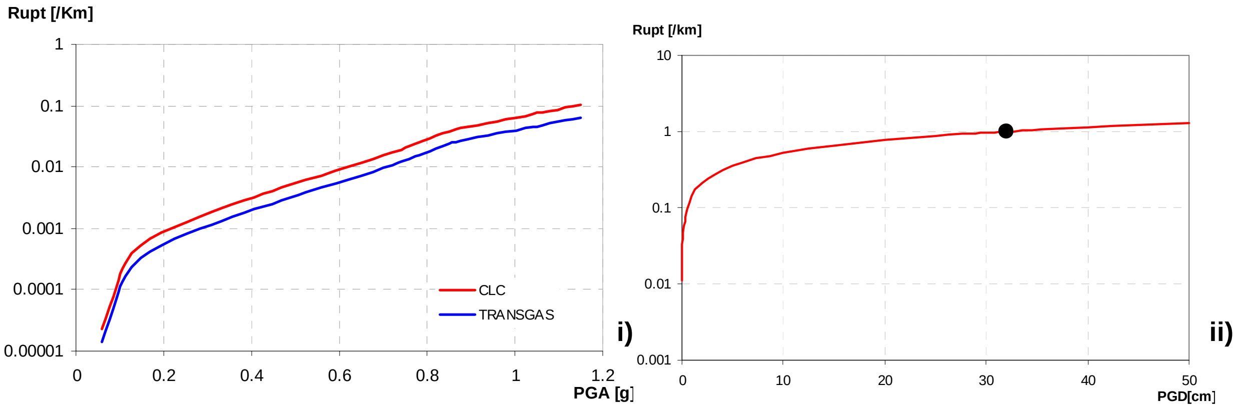


Figure 4 - Ruptures in the TRANSGÁS and CLC buried pipelines (i) PGA and (ii) PGD

Based on the observation of Figures 3 and 4 it can be concluded that the buried pipelines of the CLC network present more damages than the ones observed in the TRANSGÁS buried pipelines, considering only the dynamic effect. The reason is that the expressions adopted for the damage functions definition consider the effect of the pipeline diameter, based on the Isoyama factors. Despite the higher values of the stiffness of the TRANSGÁS pipelines their performance is better than the observed for the CLC pipelines.

For the level of seismic action considered, PGA of 1.183g and PGD of 0.32m [3], it is reached for both networks a rupture rate of approximately 1 rupture/km.

Components other than the buried pipelines

Despite the brief analysis over the buried pipelines, the application of the methodology presented emphasizes the seismic vulnerability evaluation of the components other than the buried pipelines: compression stations denominated PRP and PRM (offices of pressure reduction and measure) for natural gas network (TRANSGÁS) and the refinery, pumping plant and tank farm for the oil network (CLC). As referred before it were considered separately for all the not buried components in study, the effects of seismic waves propagation (PGA) and of the soil's permanent deformations (PGD).

For the implementation of the methodology it is necessary to establish a seismic scenario and, based in fragility curves, it is possible to evaluate the probabilities associated to each type of damage for each of the not buried components of the gas and oil networks. Therefore it is considered for the dynamic effect a PGA of 1.183g and for the effect of the soil's permanent movement a PGD value of 0.32m [3]. For this seismic scenario it is obtained, for each one of the different components, the fragility curves and the correspondent probabilities associated to each damage state.

The effects of PGA are represented in Figures 5 to 7 and the effect of PGD in Figure 8.

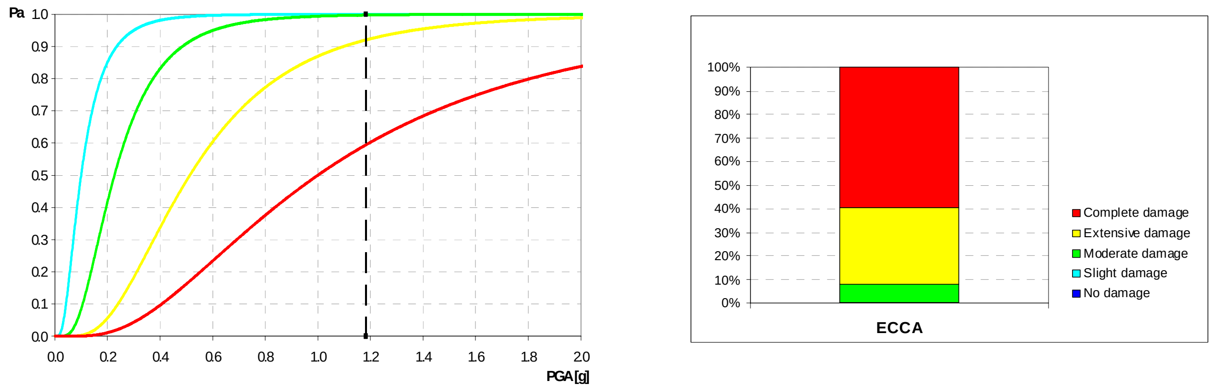


Figure 5: Fragility curves and probabilities associated to each type of damage for compression stations (TRANSGÁS) and pumping plant (CLC)

The obtained results show that, for a PGA of 1.183g, about 60% of the damages observed in the components correspond to complete damages, that means the collapse was reached. Relatively to the remaining damages about 30% present considerable extension, while approximately 5% correspond to moderate damages. One can concluded that, for this seismic scenario and for this type of components, about 90 to 95% of the damages commit their performance and operation.

The pumping plants (CLC) present the same medium values and deviation pattern [1] as the compression stations. So that it can be emphasized (Figure 5) that about 90% of the damages are quite grievous, with the great majority (60%) corresponding to the collapse of the structure.

The fragility curves and the correspondent probabilities of damage for a PGA 1.183g observed for the Sines refinery (CLC) are represented in Figure 6.

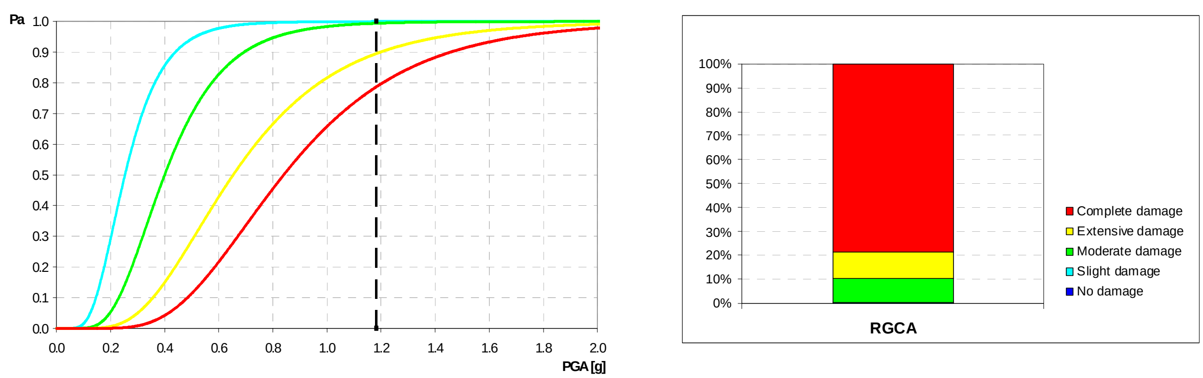


Figure 6: Fragility curves and probabilities associated to each type of damage in CLC's refinery

With the results obtained it is noticed that this component presents for the seismic action considered a more negative performance than the previous components analyzed, because about 80% of the observed damages correspond to complete damages, corresponding to the collapse of the structure. From the remaining type of damages about half (10%) correspond to extensive damages and the other half to moderate damages.

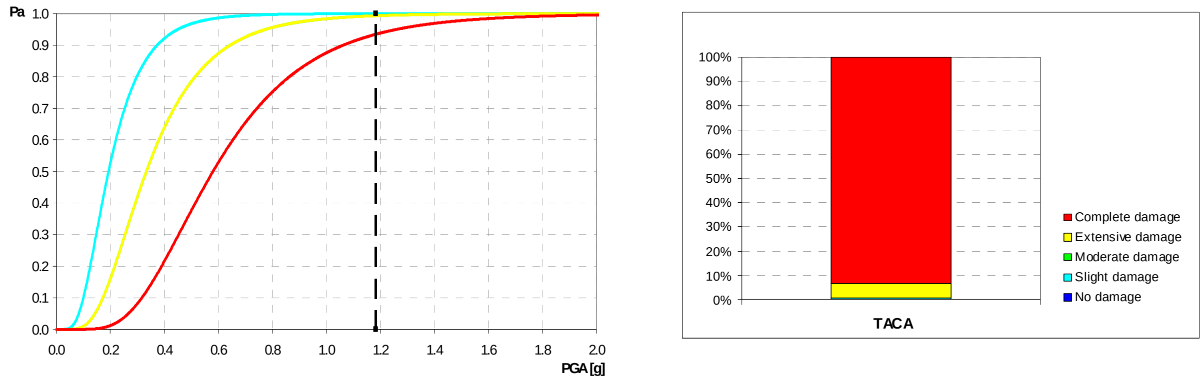


Figure 7: Fragility curves and probabilities associated to each type of damage in CLC's tank farms

After analyzing the results for the tank farms (Figure 7) it is conclude that the observed damages in these components are very high for the seismic scenario studied. Approximately 95% of the damages are considered to be complete, corresponding to the collapse of the structure. In this situation the component does not work, that means it is completely inoperative. The remaining damages (about 5%) correspond to extensive damages, which for itself make unfeasible the correct performance of this component.

In the analysis of the soil's permanent movement it is considered for all the components previously referred a PGD value of 0.32m. The results obtained are presented in Figure 8. For the effect of the soil's permanent movement only three damage states are considered. From Figure 8 it is noticed that 10% of the damages correspond to complete, half of the remaining damages correspond to a situation of no damages. For this effect and for the obtained seismic scenario adopted it is verified that in about 40% of the cases it is possible that the components maintain their performance.

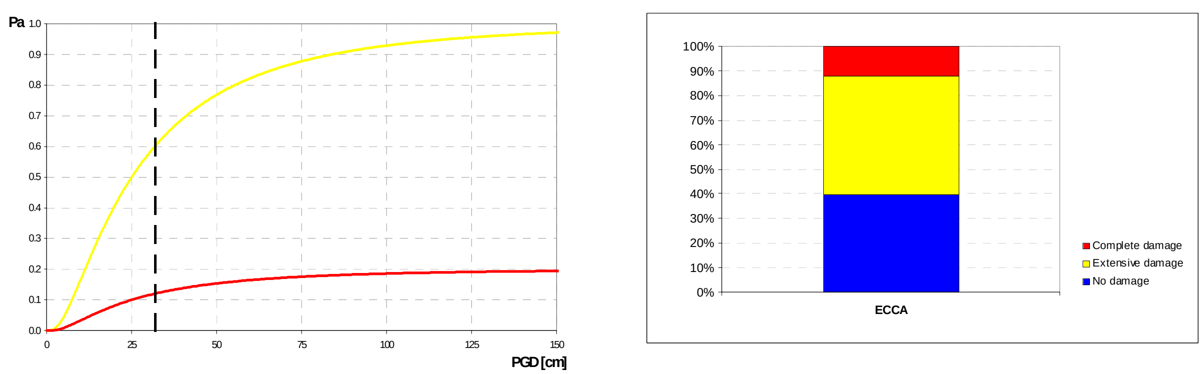


Figure 8: Fragility curves and probabilities associated to each type of damage for all the not buried components, function of PGD

CONCLUSIONS

The methodology proposed by HAZUS 99, developed to predict the damages in the different components of the gas and oil networks resulting from seismic actions, allows the assessment and evaluation of each one of the components of the system. The global evaluation of the gas and oil networks can be easily done based on a Geographical Information System (GIS). With this procedure it can be obtained the state of local damage (corresponding to a certain component) and global of the system, for certain seismic scenario.

Based on the evaluation of the components gas and oil networks, for the adopted seismic action, it was verified that:

- Considering the not buried components of the gas and oil networks the worst effect corresponds to the seismic waves propagation (PGV). On the other hand for the buried pipelines, the most severe effect corresponds to the permanent deformations of the soil [3];
- Considering the dynamic effect (PGV), the most vulnerable elements are the tank farms (from CLC network) with 95% complete damages;
- Again considering the effect of the seismic waves propagation it can be observed that from all the not buried components of the gas and oil networks the elements that present a better performance when subjected to a certain seismic scenario, are the compression stations (TRANSGÁS) and the pumping plants (CLC) with complete damages corresponding to 60% of the total damages;
- Therefore, for the seismic request and considering the dynamic effect of the seismic action, more than 60% of the damages observed for all the components are complete damages, which correspond to the collapse of the structure. In terms of probabilities occurrence it can be said that, in the eventuality of occurrence of a certain seismic action, the gas and oil networks operations became unfeasible because of the local collapse of several components.
- In terms of the permanent ground movement (PGD) it can be concluded that for all the analyzed components the damages observed are mainly extended damages (approximately 50%). In almost 40% of the cases the components do not show any damage.
- Finally it can be said that the collapse of the studied networks depends of the not buried components, for the dynamic effect and of the buried pipelines for the permanent ground deformation. The damages observed in each of the components, buried or not buried, and for each of the effect are quite grievous compromising the correct performance of the entire system.

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