Quantitative assessment of the risk associated to the transport of hazardous substances by pipeline

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The transport of hazardous substances by pipeline has a high social acceptability and is widely diffused. However, several accidents resulting in fatalities and in severe environmental contamination are reported in the literature. Conventional quantitative risk assessment (QRA) techniques are widely applied to pipeline safety analysis, but these methods seldom take into account the environmental consequences of accidental events.
In the present study a specific methodology and a software tool, TRAT-GIS 4.1, were applied to the analysis of the risk to people and environment due to pipeline transport of hazardous substances. Well known individual and societal risk plots were obtained for loss of containment of flammable and toxic substances. On the other hand, the methodology provides as well the extension of potential contaminated areas and overall cost figures expressing the severity of the expected environmental damage associated to the spill of substances dangerous for the environment. The methodology and the software were applied to several case-studies, and the results were compared to those provided by conventional methods. The analysis of the case-studies evidenced the potentiality of the method as a possible tool for decision support, in particular in the case of pipeline hazmat transport though areas where an important environmental heritage is present.

1. Introduction

The transport of hazardous materials by pipeline represents the safest mode for the on-land transfer of fluids between two plants. If this statement is confirmed by the low accident frequencies of pipeline accidents, it has to be kept in mind that the hold-up of pipeline sections - and the spilled quantities too in case of leaks - could be enormous. For this reason risk can not be considered as negligible "a priori", but has to be evaluated for each specific case.
When performing quantitative risk analysis for on-shore pipelines, the acute risk for people is generally evaluated through well established methodologies. Though another target beyond people has to be considered: the environment, and specifically the soil and groundwater, which can suffer serious damage in case of accidental spills involving liquid chemicals (CCPS, 1989). In addition to accidental spills that give rise to significant release rates and to scenarios affecting both people and the environment, for the environment also very small leaks (for instance resulting form corrosion), giving rise to small release rates, not immediately detectable in the case of buried pipelines,

can be an important source of damage. Due to the difficulty to detect such small cracks, they can last for long time before becoming evident, causing the in depth soil contamination of extended areas. Scarce attention was paid till now to the environmental risk of pipelines, and, as a consequence, no general comprehensive methodological approaches can be found in literature.

The research presented in this paper tries to close this gap. First of all a description is given of a new comprehensive procedure for the evaluation of the risk for people and environment due to pipelines. After highlighting the theoretical fundamentals of the procedure, details are presented about its implementation in the TRAT-GIS 4.1 software, a ready-for-use tool working on a Geographical Information System (GIS) which allows to efficiently manage all geographical related data. Examples of input and output data are given to show the potentiality of the software.

2. Description of the methodology

The methodology for the evaluation of risk to people and to humans consists of different steps. Some steps are common for both targets, others are specific for one of them. As a common first step it is necessary to describe how the pipeline may break. Usually two or three loss of containment events or LOCs (i.e. a "pinhole", a medium hole and a full-bore rupture) are chosen as a function of the pipeline diameter. For these LOCs reliable data about occurrence frequencies are available in literature, derived from historical data. For each LOC the source term has to be evaluated through well established consequence analysis models, as a function of the hole diameter, of the properties of the substance and of its pressure conditions inside the pipeline. In addition the duration of the release and the totally spilled mass can be estimated and, if a liquid phase is released and a pool is formed, the pool dimensions can be calculated. Afterwards through post-release event trees different final outcomes (for instance toxic plumes or puffs, pool-fires, fireballs, jet-fires, flash-fires, vapour cloud explosions, non-ignited pools) can be associated to each LOC and the occurrence frequency of each final scenario can be calculated. Flammable and/or toxic gases and liquids cause scenarios affecting people. Furthermore, if a pool is formed (i.e. in the case the spilled substance is a liquid), the spill can pose a risk also to the environment, and in particular it can give rise to scenarios affecting the soil. At this point the procedure becomes different depending on the target, since the characterisation of the final outcomes affecting people is different from the description of the scenarios affecting the soil.

If the risk to people has to be evaluated, the area around the pipeline has to be characterized through meteorological conditions, in terms of Pasquill class and wind velocity. For each final scenario affecting people the spatial distribution of the physical effects (namely radiation, overpressure and toxic concentrations) has to be evaluated for all meteorological classes. This phase of the procedure can be performed with traditional consequence analysis models. In a following step, damage models (for instance probit equations) enable the conversion of the adverse effects into death probabilities. Finally a risk recomposition has to be performed, combining death probability distributions and occurrence frequencies to obtain the local risk distribution around the pipeline. If population data in the impact area of the pipeline are available, also societal risk can be estimated, as *F/N* profiles, being *F* the cumulated frequency of having a number of fatalities equal or greater than *N*.

The adverse effects to soil of a spill will be present if a pool is formed and remains for some time over the terrain, so that the substance can penetrate inside the soil. This scenario is always present in the case of non-flammable liquids dangerous for the environment.

In the case of flammables, a pool leaking into the soil will be present only if the substance does not immediately ignite, since, in case of ignition, the substance will be consumed by the fire due to the high values of the burning rate. In the case of an enduring pool, the liquid will migrate from the surface into the soil. Usually evaporation is a slower process than infiltration and so it can be neglected.

Thorough soil pollution models, the extension of the contaminated zone can be evaluated for each LOC, as a function of the pool dimensions and of the environmental data that characterize the impacted soil. For the purpose of estimating an environmental risk index, a rough description of the soil layers and of their pollution mechanism can be sufficient: the liquid will penetrate into the terrain, crossing the cover layer. Then it will leak into the so-called vadose zone and potentially get to the groundwater table (especially if the table is at low depth and the permeability of the vadose is high), where the saturated zone begins. At this point the infiltrated liquid gives rise to a plume expanding in the water flux direction. The whole infiltration process can be described through simple soil and groundwater contamination models available in literature. Though, while the scenarios affecting people generally take place within a few minutes from the beginning of the release so that no action can be undertaken to avoid them, the infiltration scenarios have a slower dynamic. For this reason specific countermeasures can be put in use to limit the extension of the contaminated area.

Remedial actions are represented first of all by early excavation, having the purpose to avoid or at least to limit the in depth infiltration of the substance. As a second remedy, physical and hydro-geological barriers can be installed. Lastly clean-up techniques can be applied. As a consequence of the intervention of an emergency team, the extension of the contamination does not depend only on the spill scenario, but it is also a function of the timing of excavation and of barrier placement. It has to be noted that, while the penetration of the liquid of the pool into the cover layer will always occur, the in depth infiltration into the vadose zone till the groundwater layer depends on the features of the terrain and of the timing of remedial actions. If, for instance, the soil permeability is small, the groundwater layer lies at great depth and the intervention of the emergency team is rapid, the liquid will not reach the lower layers of the vadose zone and the saturated zone: in this case only the cover layer and the first part of the vadose zone will be contaminated.

In order to estimate the consequences of the environmental scenario, plausible assumptions have to be adopted for the starting times of remedial actions. The output of these contamination models are the volume of contaminated soil V_{soil}, expressed as the sum of the volumes of the excavation zone V_{exc} and of the vadose zones V_{vad}, and the surface of the saturated groundwater zone affected by contamination A_{gw}. These data represent the environmental consequences of the pipeline LOCs; combining them with their occurrence frequencies, it is possible to obtain the F/V_{exc}, F/V_{vad} and F/A_{gw} curves, expressing the cumulated frequency F of having accidents causing soil excavations of volumes equal or greater than V_{exc}, contaminations of volumes of the vadose terrain equal or greater than V_{vad} and groundwater contaminations of surfaces equal or greater than A_{gw}. These curves represent environmental risk measures.

Though, since volumes can not be compared to surfaces, they are not immediately comparable to each other, and furthermore, volumes and surfaces can not be compared to human fatalities. In order to do this, a further step is necessary. Taking from literature the unitary cost of excavation UC_{exc} and of soil treatment UC_{vad} (expressed per unit volume of soil) and of groundwater clean-up techniques UC_{gw} (expressed per unit surface), the F/V_{exc}, F/V_{vad} and F/A_{gw} curves can be converted into F/M curves, being F the cumulated frequency of having an economical damage equal or greater than M. In fact by simply multiplying the abscissa values of each curve by the specific unitary cost value, the F/M_{exc}, F/M_{vad} and F/M_{gw} curves are obtained. The F/M_{exc}, F/M_{vad} and

F/M_{gw} curves can be summed to obtain a unique environmental risk measure, the F/M_{env}. In a similar manner, if the Human Life Value *HLV* is available, by multiplying each value of *N* by *HLV*, the *F/N* curve too can be converted into a F/M_{fat} curve. In this way the F/M_{fat} and the F/M_{env} curves, referring respectively to human fatalities and to soil contamination, can be compared and eventually summed, to obtain a unique pipeline risk index.
If, in addition to the LOCs affecting both people and environment, also a non detectable crack affecting only the environment is taken into account, the environmental risk measures can be evaluated for it following the previously described procedure. Though the consequence evaluation has to be performed without taking into account remedial actions and assuming the infiltration process as stationary, due to its long timing.

3. Implementation of the methodology in the TRAT4-GIS software

The previously described risk evaluation methodology has been implemented in a specific software named TRAT4-GIS. This tool, initially developed for the transportation risk analysis of road and rail hazmat transport, has recently been extended to pipelines. For this mode of transport it performs the calculation of the risk to people producing the well known individual and societal risk plots, and, in addition, the calculation of the risk to soil. The software uses a Geographical Information System (GIS) in storing, managing and displaying (through maps and tables) all the geographical-related input and output data.

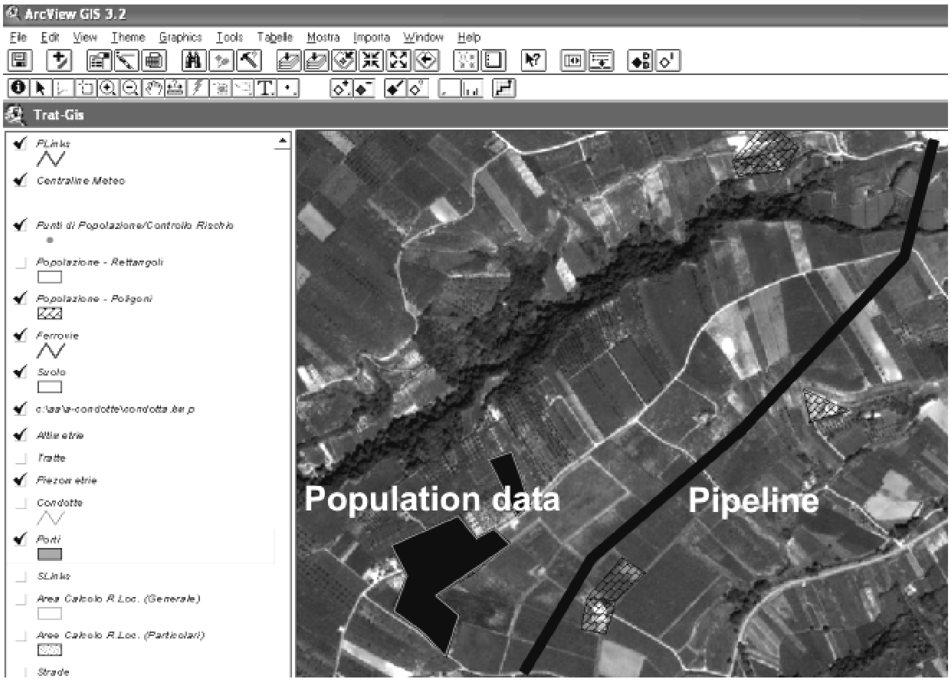

Figure 1: TRAT4.1-GIS software: GIS interface for the introduction of geographical related data

Through the software the pipeline risk evaluation methodology has been applied to several Italian case-studies. For the seek of brevity it’s not possible to describe in detail these applications. For this reason hereon only some figures are presented about the module performing the environmental risk evaluation, with the aim to highlight the features of the software in the data introduction phase and in the presentation of results. In Figure 1 the introduction of some data through the GIS interface is shown. The pipeline path can be easily drawn on a photo or a map.

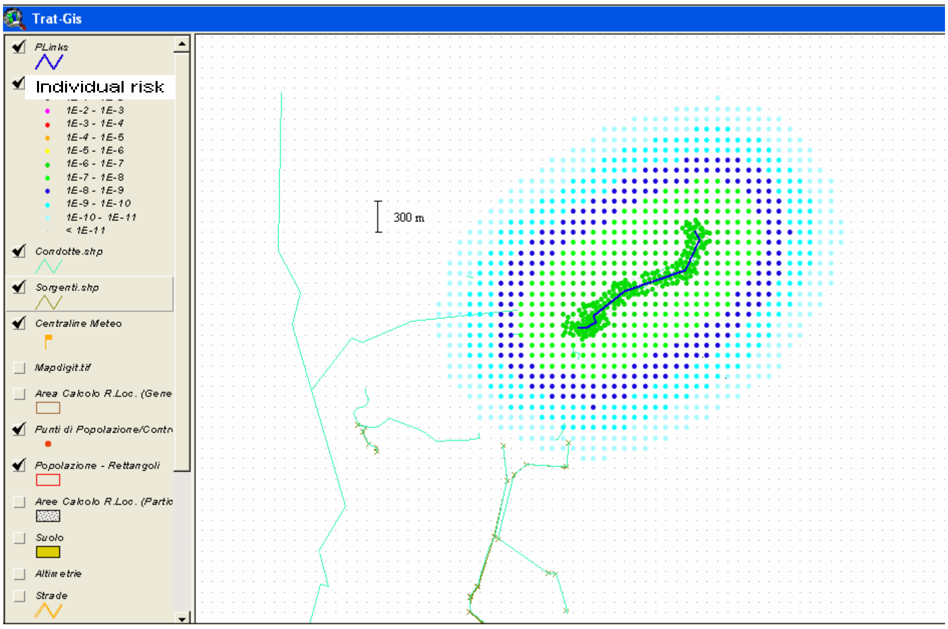

Figure 2. TRAT4.1-GIS software: results of a case-study – individual risk due to H_2S dispersion following the rupture of an oil pipe.

The population data can be introduced for the calculation of societal risk. Further the soil has to be characterized through two parameters. The first one is represented by the hydro-geological conductivity; the software requires a unique average value for the layers between the surface and the beginning of the saturated zone. The area along the pipeline has to be subdivided in polygons, which have to be drawn on the map, each polygon having a specific conductivity value. The second datum is the depth of the groundwater table with respect to the surface in the area around the pipeline; this depth is given for a discrete number of points in the pipeline area, for which the altitude on the sea level and the depth of the groundwater table with respect to the sea level have to be specified.
Figure 2 shows the results of a conventional risk analysis concerning a hydrogen sulphide dispersion following the rupture of a raw oil pipeline connecting an oil well to the upstream primary treatment facilities.
Figures 3, 4 and 5 show examples of results referring to environmental risk are reported. Figure 3 shows the environmental damage in a specific point of the pipeline. This damage is expressed in two ways: as volume of the excavation zone, as volume of the soil subject to decontamination and as the area of the contaminated groundwater zone. By multiplying each physical effect by the corresponding unitary cost of the remedial actions, a monetization of the environmental damages can be obtained; the percentage values of monetized damage with respect to the total cost of the environmental contamination are depicted in a cake diagram.

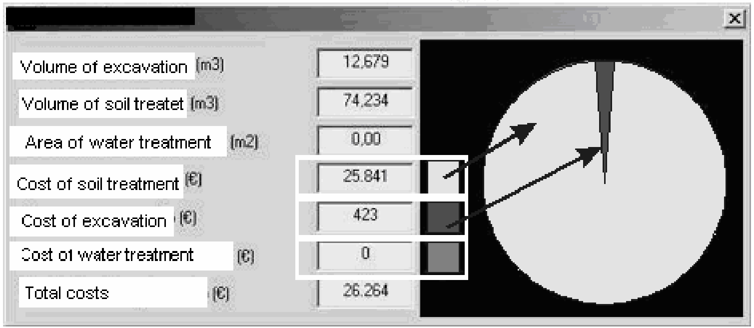

Figure 3. TRAT4.1-GIS software: environmental damages for a specific point of the pipeline

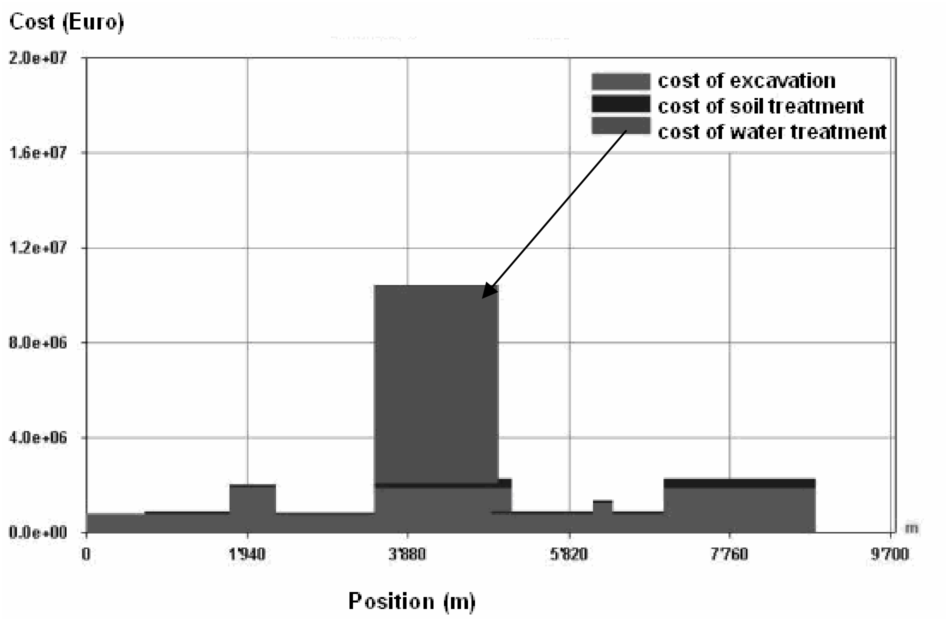

Figure 4. TRAT4.1-GIS software: cost evaluation of the environmental damages along the pipeline

These cost values (excavation, soil decontamination, decontamination of the saturated zone) can be obtained for each point of the pipeline. Dividing the pipeline in small sections, they can be plotted along the pipeline path for each of these segments, as shown in Figure 4.

In Figure 5 an example of F/M profiles is shown: the F/M_{exc} curve, the F/M_{vad} curve, and the F/M_{gw} curve. The sum of these curves gives the F/M_{env} curve.

4. Conclusions

A specific software for the analysis of the risk in the transport of hazardous substances was extended to the assessment of the risk due to pipeline transportation of hazmat. In particular, beside the conventional calculations of individual and societal risk, the software also provides data for the estimation of the environmental damage that may follow pipeline failures and leaks. Several applications to case studies evidenced the flexibility of the tool and the value of the integrated approach developed for the assessment of risk for persons and for the environment.

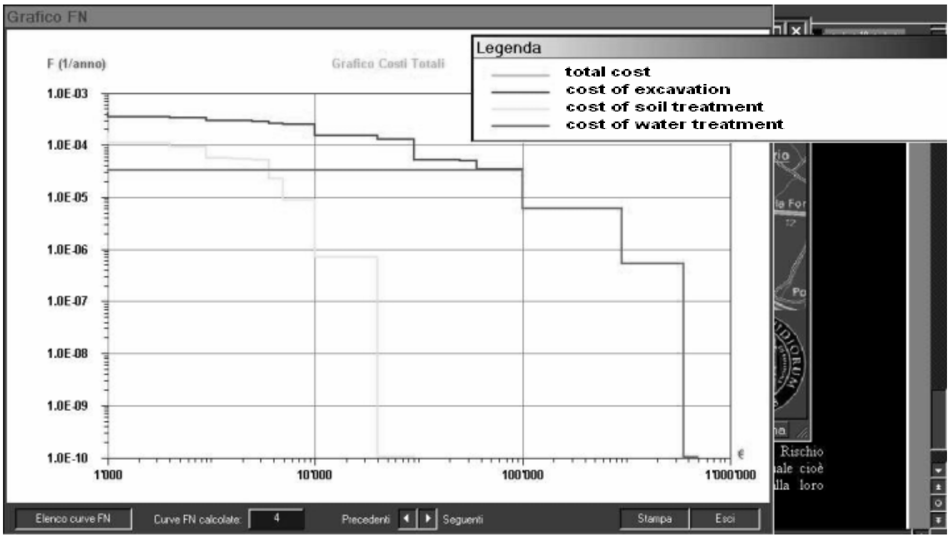

Figure 5. TRAT4-GIS software: example of F/M_{exc}, F/M_{vad} and F/M_{gw} curves

5. References

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