MULTIDISCIPLINARY EFFORTS IN SEISMIC RISK ASSESSMENT AND RETROFITTING OF EXISTING FACILITIES CONTAINING HAZARDOUS MATERIALS

Alexander Avihu COHEN[1], Yaron OFFIR[2], Anat TZUR[3], Alex SHOHAT[4] and Amos SHIRAN[5]

[1] *PhD (Chemistry) Chief Executive Officer, Hazmat LTD, 19th Hamelacha St. Rosh Haayin 48091,Israel*
Email: alex_cohen@hazmat.co.il
[2] *M.Sc Structural Engineer, Partner , Yaron-Offir engineers Ltd, Technion campus, Haifa 32000, Israel*
Email: yaron@kedmor-offir.co.il
[3] *B.Sc, Hazmat LTD, 19th Hamelacha St. Rosh Haayin, 48091, Israel*
Email: anat_t@hazmat.co.il
[4] *B.Sc Structural Engineer, Yaron-Offir engineers Ltd, Technion campus, Haifa 32000, Israel*
Email: alex@kedmor-offir.co.il
[5] *M.Sc Structural and Geotechnical Engineer, Amos Shiran Earthquake Engineering, Hayogev 19232, Israel*
Email: amoshiran@gmail.com

ABSTRACT

Two years ago, the Israeli Ministry of Environmental Protection (MOE) required from the top-20 most hazardous facilities in the industry sector to asses their capability to withstand a significant Earthquake.
Clearly, the combination of: 1) stochastic seismic phenomena; 2) the dangers of a process involving hazardous materials; and 3) the fact that existing processes in the industry were rarely designed according to a seismic standard; poses a highly significant risk. Moreover, the cost of retrofitting an existing facility is considerably high. Therefore, a state-of-the-art engineering, e.g. displacement-based considerations and non linearity behaviour both in the ground and in the upper structures and facilities, and a careful design, yet cost-effective, had to be set.
By taking advantage on the pilot study initiated by the Israeli MOE, the authors developed a practical probabilistic methodology for decision making concerning the retrofitting of processes containing hazardous substances vulnerable to seismic events.
The proposed methodology is based on the quantification of the damage due to earthquakes, calculation of the retrofitting cost and using the proportion between these two values as an acceptance criterion.
The proposed approach has been used for risk assessment in various industries such as chlorine plants, fertilizers plant, refrigerating facilities in the food industry, pharmaceutical industries and other chemical industries.
The case studies shown in this article demonstrate how the close collaboration of engineers from the wide disciplines involved; stimulate appropriate and realistic solutions, perhaps unusual sometimes.

KEYWORDS: environmental risk, seismic risk, retrofitting, existing facilities, chemical industry, performance based engineering

1. INTRODUCTION

It is well understood that significant structural damages to a facility containing hazardous materials may lead to a major chemical incident and adverse environmental impacts such as fire, explosion or dispersion of a toxic substance. Regardless of the cause of the structural damage it should be prevented and the consequences should be well mitigated to minimize all kinds of losses in major chemical incidents.
Earthquakes as a potential cause of severe structural damages to many kinds of structures and buildings, pose a more complex challenge whenever it comes to facilities containing hazardous materials, in particular to facilities in existing plants.

Retrofitting of existing facilities containing hazardous materials requires multidisciplinary skills. It takes not only the obvious engagement of structural engineers planning the actual retrofitting and geotechnical experts determining the seismic risks, but also other varied aspects: chemical engineers dealing with process means for prevention and mitigation of hazardous materials incidents, chemical risk assessment experts assessing the possible impact of the loss-of-containment of hazardous materials, operators and maintenance workers determining the operational needs and limitations, and more.
The most straightforward approach would be to prevent, by all means, all kinds of structural damages in hazardous materials facility. Yet, 100% prevention in an area prone to earthquakes might be a very expensive mission where it comes to complex facilities such as existing plants.

This conflict between the necessity to protect the environment on the one hand, and the enormous costs of retrofitting on the other hand, needs to be resolved by policy makers. Or in other words, seismic retrofitting should be proportional and as cited from **Porush and Bachman** (2003):
"It is not politically feasible (nor is it desirable) to replace the industrial infrastructure of coastal California. Any attempt to suggest that because such facilities do not meet the latest codes that they all must be strengthened, or worse, torn down, would result in essentially nothing being done, and nothing being accomplished in reducing current seismic risk".

In this paper we present the application of a policy guidelines developed by the Ministry of Environmental Protection in Israel (**A. Warszawski and D. Yankelevsky,** 2005) that attempts to define quantitatively the proportionality between the potential damages due to earthquakes and the prevention (such as prevention by retrofitting, taking engineering measures, taking administrative measures and more) in existing facilities containing hazardous materials.

2. METHODOLOGY

The basis of the methodology applied has been drawn by Warszawski and Yankelevsky for the Israeli National Steering Committee on Earthquakes and adopted as a guideline for a pilot study by the Ministry of Environmental Protection.
In the guideline the authors stated that the cost of retrofitting may be limited by the direct cost of the damages caused by an earthquake. The reference earthquakes for this purpose would be the worst earthquakes in magnitude expected within time periods of 500, 1000 and 2500 years.

Based on this policy, we constructed the following methodology for a typical chemical plant:

2.1 Selecting a Process to be Analyzed

First screening. The plant was divided into processes. The division was made such that each process will contain a regulated hazardous substance, (namely extremely toxic and or highly flammable hazardous material) in a quantity exceeding a given threshold. Processes not meeting this initial criterion were excluded.
Second screening. Only processes exhibiting a life threat beyond the plant boundaries were considered.
Third screening. For the pilot study, only one of the processes remained after the above screening was chosen, based on the plant's considerations, to demonstrate the methodology.

2.2 Breaking of a Process into Scenarios

The analyzed process was broken down into its main elements – tanks, pipeline, pumps etc. For each element we developed a set of incidents that may lead to loss-of-containment (LOC) scenario. For simplicity we used generic incidents, e.g. tank rupture, full bore rupture of a pipe, holes 10 mm in diameter in the tank's shell and more (for a generic list of feasible scenarios see for example **CPR 18E**, 1999).
The worst-case impact of each scenario was modeled by employing commonly used designated models (e.g.

ALOHA or EFFECTS), where the worst-case impact has been defined by the lethality of at least 1% of the population exposed to the impact for 10 minutes or more. As the last screening tool, only scenarios where the worst-case calculated distance exceeded the plant's boundaries were considered.

2.3 Financial Damage Assessment

The mean damage of each LOC incident was calculated by weighing the probability of each person within the impact-range of the scenario to die or to get hospitalized as direct result of the scenario considering variable time-of-day, wind direction and speed, meteorological stability, terrain, population, the return period of the earthquake, passive mitigation measures used in the process and more. The weighing procedure assumed a randomly occurring earthquake without taking into account neither predetermined alarms nor human actions taken immediately after the occurrence of the earthquake. As a conservative assumption we did not subtract the number of casualties caused directly by the earthquake.
The outcome of this assessment was the casualties' expectancy, namely the mean number of deaths and injured persons in the scenario.
In order to translate the number of casualties into costs, we used a predetermined estimation of the cost of loss of life in Israel which was about 1,200,000 USD, similarly the cost of recovering was estimated to be 3,000 USD.
Within this framework we were able to place a price tag for each scenario.

2.4 Seismic Hazard Assessment

Following the CalArp guidance a specific seismic hazard evaluation should address and quantify, where appropriate, the following seismic hazards: 1) ground shaking and local site amplifications effect; 2) fault rupture; 3) liquefaction and lateral spreading; 4) seismic settlement; 5) landslides; and 6) tsunamis.
With this information in hand the structural engineer can proceed to the next step – *retrofitting assessment.*

2.5 Retrofitting Assessment

The retrofitting assessment consists of three levels of assessments:
1) Starting with onsite review the main seismic vulnerable structures are identified. Together with the plant's personnel the functionality and operability constrains of possible upgrading is then determined.
2) With the information gathered from site and according to the seismic hazard assessment, preliminary retrofitting alternatives are suggested. The structural engineer and the hazardous-materials expert together with the plant's engineering department examine each recommendation for retrofitting considering the following aspects:

- Is it possible to achieve the same level of protection (or risk reduction) by employing a process-measures rather than structural retrofit?
- Will this retrofit scheme reduce the number of casualties well below the acceptance criteria?
- How will this retrofitting solution interfere with the daily life in the plant?
- Are there additional benefits for accepting a proposed retrofitting solution, for example keeping the process operable even after an earthquake?

By repeating this brain storming process, the team comes up with a generally accepted retrofitting solution.
3) In this stage a more comprehensive analysis takes place according to the appropriate and relevant code (e.g.: ASCE 41-06 for building-like structures, ASCE 7-05 for nonstructural elements, API 650 for steel flat-bottom tanks etc.) and if necessary a soil-structure-interaction analysis is preformed. And finally, the retrofitting solution may undergo detailed design and could be reasonably priced.

2.6 Decision Making

This is the core of the methodology, which gives the proportionality aspect of the proposed retrofitting solution. The cost of the damage, namely the price tag of each scenario was compared to the retrofitting price calculated at 3 return periods of an earthquake: 500, 1000, and 2500 years.
Within this comparison decision became easy: whenever the cost of retrofitting exceeded the cost of damage, retrofitting became disproportional and therefore not required; while if the cost of retrofitting was less or equal to the cost of damage, retrofitting became a requirement.

3. CASE STUDY 1: AMMONIA PLANT

The following case study will demonstrate the actual implication of the methodology. It will elaborate the work done at an Israeli dairy, near a densely populated area, and will demonstrate the problems encountered on field, the collaboration between the different specialists, and the creative solutions which were given.

3.1. Defining the Process to be Analyzed

The only regulated substance in the dairy was ammonia as a refrigerant. Ammonia is classified as a toxic gas. However, there were two separate refrigerating systems in the dairy; each one of them contained enough Ammonia to be considered as a regulated process. After defining the two regulated processes, it was determined that both were possible candidates for seismic risk assessment as they both pose a potential risk to people outside the plant. The dairy chose to analyze the larger refrigerating system first, since it was potentially more hazardous.

3.2. Hazardous Materials Risk Assessment

The risk assessment was conducted as described in section 2.3 above. 12 different Loss-of-Containment scenarios were analyzed. The largest lethal range in the worst case scenario modeled was about 1500 m.

To get information on the population that was as accurate and up-to-date as possible, the population had to be identified and mapped on field wherever possible. Several trips were made by foot, to cover the densely populated 1,500 m range. The population was found to consist of residential neighborhoods, industrial zones, shopping and recreation areas, and schools. Some basic assumptions were made, based on statistical information: e.g., that an average family in Israel consists of 4 persons. The number of people in each building/area was multiplied by the relative amount of time they spend in that building/area. The total population in the hazardous range was estimated at 30,000 people at any given hour.
Table 1 demonstrates the numbers of casualties and the expectancy of financial damage in 3 of the 12 scenarios.

Table 1. Numbers of casualties and damage cost in three representative scenarios.

LOC Scenario	Casualties	Damage Cost (M USD)
Rupture of Ammonia Receiver	19	24.6
Release of Entire Content of Ammonia Receiver within 10 Minutes	145	195
Leak from a 10 mm Diameter Hole in Ammonia Receiver	16	21.5

3.3. Retrofitting Solutions

One of most hazardous scenarios needed to be prevented was a collapse of a water tower standing on a very weak-story platform. Collapse of this tower might break a pipe containing liquefied ammonia and damage the near by ammonia machinery room. It was not possible to interfere in the intermediate space between the weak story columns as this space was extensively used for the system cooling plates and some pumps. The dairy is considered as an essential plant and therefore may not be shutdown for long periods. These constrains had dictated a limited retrofit by FRP lamination of the columns which would increase ductility together with capacity enlargement by steel plates under the FRP. This creative solution was found however to be disproportional.

Unusual retrofit solution was suggested in the form of "cage" cover for ammonia liquid receiver (**Figure 1**). This was designed to withstand high dynamic impact caused by the collapse of a heavy condenser that is expected to fall from the roof at a strong seismic event. It was found that a complete retrofit of the fragile roof structure above to prevent the collapse of the condenser was too costly and disproportional.

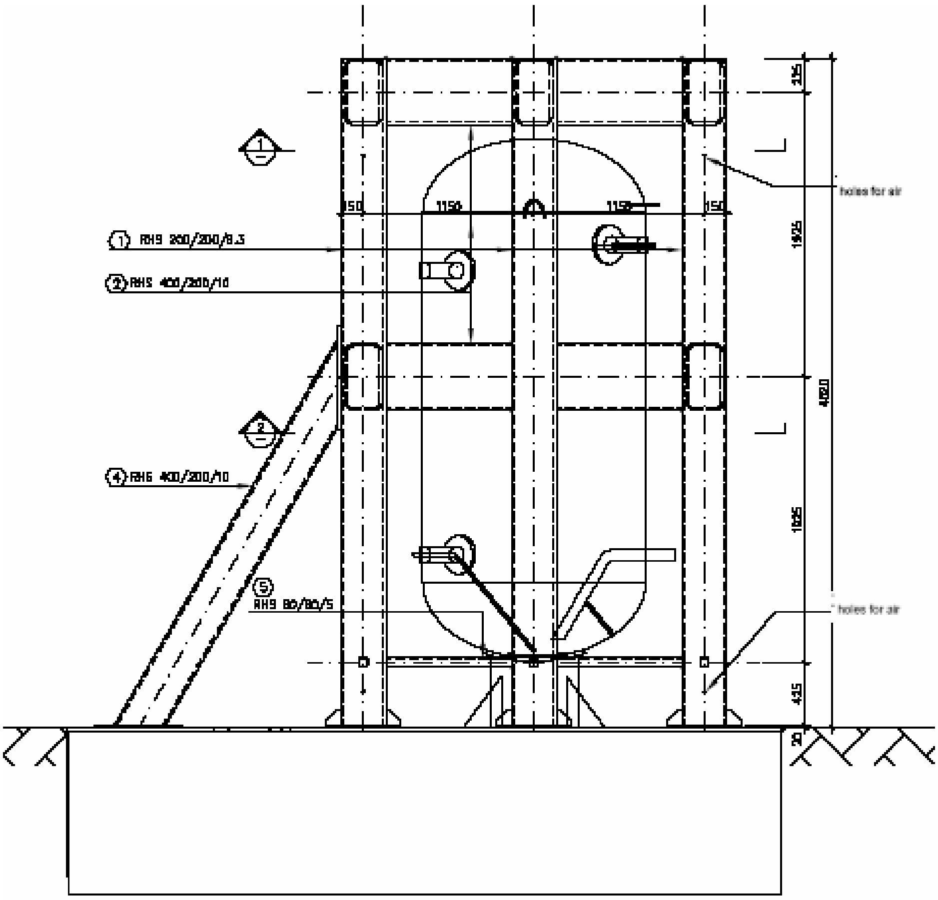

Figure 1: "cage" cover for ammonia liquid receiver to withstand dynamic impact strike

3.4. Conclusions

The estimated total cost of structural retrofitting was about 500,000 USD. As a result of the cost-effective analysis, it was determined that the only applicable retrofitting would be the installment of extinguishing sprinklers and "cage" covers for the tanks in the machinery room, which would cost about 85,000 USD only. Protection against all of the possible scenarios was found disproportional and therefore unnecessary.

4. CASE STUDY 2: CHLORINE STORAGE TANK

4.1. Risk Assessment of the Analyzed Process

This plant had several batch production processes, containing various regulated substances. The process chosen for retrofitting was a chlorination process, composed of a storage tank, a vaporizer and the pipe between them. Five LOC scenarios were analyzed, with the worst-case lethal range being 650 m. The damage of the different scenarios varied between 270,000 and 7,000,000 USD.

4.2. Retrofitting Solutions

Figure 2 shows the current state of tank in process. The tank had to be replaced by new full similar tank every 30 hours, so fixing it to the concrete wall of the room was not practical. The chosen solution **(Figure 3)** suggested installation of steel rings on existing bottom round steel supports, preventing longitudinal movement of tank. L normal profile stopper is installed downstream in line to prevent accidental longitudinal release if "first defense line" was crossed. Horizontal restrainers installed both on concrete wall and on new steel beam attached to current steel frame.

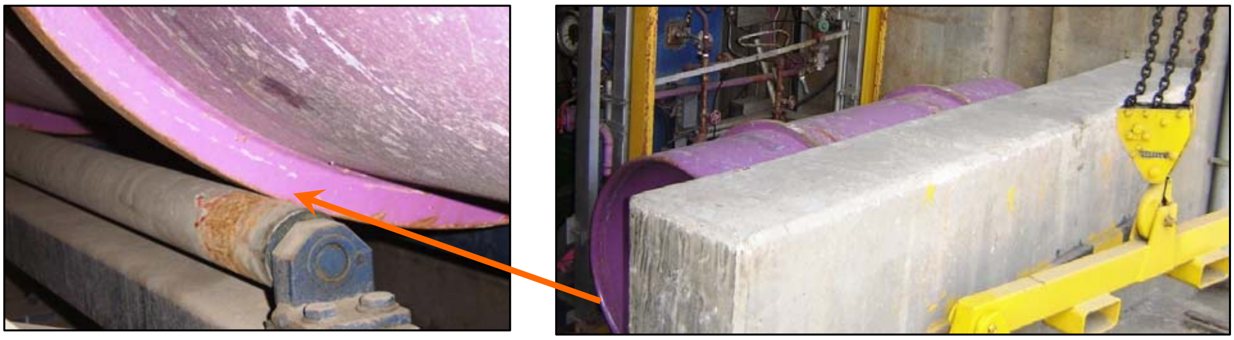

Figure 2: general view of 1.0 ton liquid chlorine tank before retrofitting (right). Existing round strap of tank lying above steel rounded support (left).

4.3. Conclusions

Two retrofitting alternatives were suggested: one that would cost about 10,000 USD, and one that would cost about 9,000 USD. Both were proportional. After reviewing various considerations, including the predicted disturbance to routine operation, the plant has chosen to implement the second
(and also slightly less expensive) alternative.

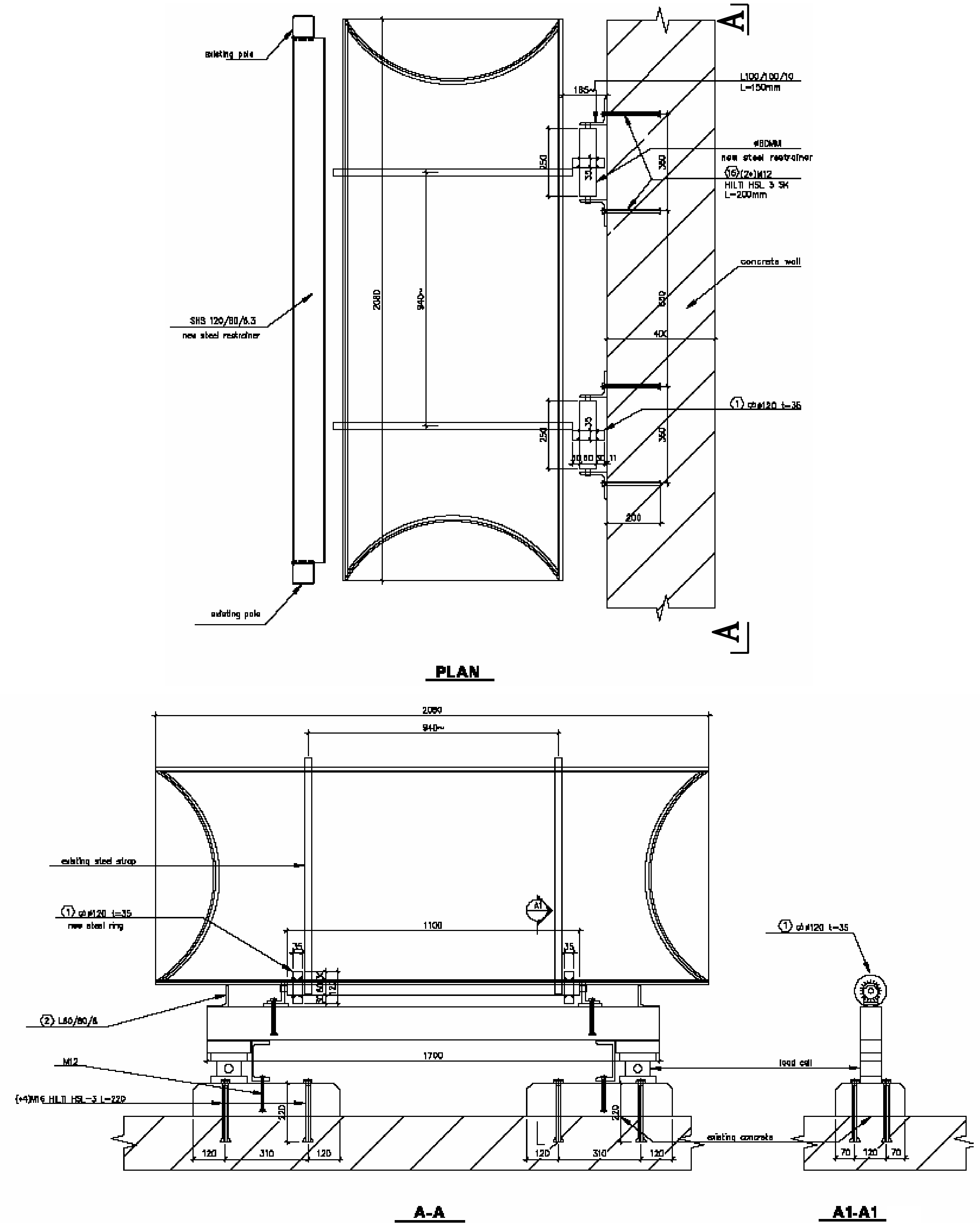

Figure 3: plan (top) and sections (bottom) describe the suggested retrofitting,

5. DISCUSSION

Case study 1 demonstrates the extreme difference that can exist between 100% prevention and a proportional retrofitting – the applicable cost in this case was less than 1/4 of the total estimated cost. On the same time, it shows that when a complete retrofit is too costly to implement, it doesn't necessarily have to be "all or nothing": creativity in the proposed retrofitting can give solutions to some of the possible scenarios at a feasible cost, even if not to all of them.

In case 2 some other considerations, other than the cost itself, were taken into account when deciding on the preferred retrofitting: the two proposed alternatives were proportional, however, one was more convenient to the plant in the aspect of the disturbance when performing the retrofitting and the routine operation afterwards.

Comparing the two cases, it can be seen that the higher the damage is, the more expensive the applicable retrofitting can be. Both cases, however, demonstrate the use of the comprehensive methodology: selecting a process to be analyzed, breaking the process into scenarios, financial damage assessment, seismic hazard assessment, retrofitting assessment and finally – making a decision.

6. SUMMARY

It has been demonstrated that the proposed methodology is general, applicable and most important could be fine-tuned by policy makers by manipulating the acceptable ratio between the cost of damage and cost of retrofitting, namely by setting an acceptance criteria on the proportion between the two factors.
The joint-effort of chemical, geotechnical, mechanical and structural engineers enabled provision of a reasonable assurance that the undesirable poor seismic response of existing plant containing hazardous substances will not occur under major earthquake. This is achieved through identification, prioritisation and retrofit of seismically vulnerable processes based on the various loss of containment scenarios. The effort is intended to reduce the risk of catastrophic failure to a large extent by reducing uncertainties and increasing resistance to strong earthquake ground motions and in addition to optimise owner expenditures, in terms of engineering and construction retrofit costs.

REFERENCES

- ALA, American Lifelines Alliance (2002), Seismic Design and Retrofit of Piping Systems, Written under contract to the ALA, a public-private partnership between the Federal Emergency Management Agency (FEMA) and the American Society of Civil Engineers (ASCE).
- ALOHA 5.4.1, Developed by Office of Emergency Management, EPA and Emergency Response Division, NOAA.
- API 650, (2005), Welded storage tanks for oil storage, *American Petroleum Institute Standard*, Washington D. C.
- ASCE 7-05 (2005) Minimum Design Loads for Buildings and Other Structures, *American Society of Civil Engineers -ASCE Standard USA.*
- ASCE-SEI 41-06 (2007) Seismic Rehabilitation of Existing Buildings, *American Society of Civil Engineers-ASCE Standard USA.*
- CalArp Guidance for California Accidental Release Prevention Program (2004), Guidance for CalARP Seismic Assessments, *Region 1 Local Emergency Planning committee (LEPC)*, California.
- Committee for the Prevention of Disasters (1999), Guidelines for quantitative risk assessment, Sdu Uitgevers, The Hague.
- EFFECTS 4 (April 2000), TNO, Department of Industrial Safety, The Netherlands
- Porush, A.R and Bachman, R.E. (2003) CalARP seismic evaluation guidelines for existing facilities containing hazardous materials; *Proceedings of seminar on seismic design performance and retrofit of nonstructural components in critical facilities*.
- Warszawski, A. and Yankelevsky, D. (2005). A method for determining the level of risk for Earthquake retrofitting of existing industrial facilities containing hazardous materials (in Hebrew).