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Reducing the seismic vulnerability of existing elevated silos by means of base isolation devices

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A B S T R A C T

Industrial silos are used for storing a huge range of different materials. In the last decades, many of these structures were damaged by natural events, among which the earthquakes were the most significant. Indeed, numerous industrial plants have been built in the territories with high seismicity risk. Most of these plants have been designed and built before the latest updates of the seismic design codes took place, hence their current seismic reliability is questionable. In order to avoid future economic, life-safety and environmental troubles that can be caused by the collapse of these non-building structures, specific retrofitting solutions should be developed and implemented urgently. This paper shows the feasibility of the seismic isolation solution on a typical case study. Seismic vulnerability of an existing industrial steel silo system has been investigated, and a retrofitting solution has been proposed making use of the curved surface single sliding pendulum devices. Incremental dynamic analysis method has been used to compare the performance of the original and the retrofitted solutions. Structural benefits of the seismic isolation solution have been quantified in terms of inelastic deformations, base shear, inter-story drifts and isolator displacements. The seismic behaviour of the original and the retrofitted structure has been compared by means of fragility curves.

1. Introduction

Storage elements employ a predominant part (over 90% of the total surface) of the industrial plants. Silos are the industrial storage components that are used for storing a huge range of different solids and liquids such as grain, cereals, chemical agents [1]. Generally, these structures are made of steel, and they can be both lying on a foundation (anchored or unanchored ground supported silos and tanks), or elevated (supported by a structural frame) as shown in Fig. 1 [2]. Their shapes can be complex because of the vent, lifting and ensilage systems, and several technical details such as conveyor belt, cochlea, symmetrical or unsymmetrical hopper.

Silos are special structures that are subjected to several loading conditions, which may collapse in unusual modes. They have been considered as “non-building structures” [4], and the main attention has been so far paid on their functionality under service conditions. Their structural components have not been under focus for accidental loads such as earthquakes. The seismic behaviour of these structures is very complex and not well assessed so far. Yet, their damage or collapse can have very devastating direct (the loss of the container and of the stored material, or its contamination) or in-direct (relative replacement costs, clean-up and possible environmental damage, injury or loss of life) consequences [5]. To guarantee human life safety and optimize the use of resources, the effort spent for the evaluation of seismic risk for the existing buildings and mitigation strategies for its reduction [6], should be extended also to the industrial systems.

In ground-anchored storage systems with liquid content, earthquake loading generates an extra horizontal pressure on the silo wall, which is also influenced by the material characteristics of the content. These conventional liquid storage tanks have been studied numerically and experimentally by several researchers, to understand their seismic behaviour. Housner [7] proposed an analytical model simulating the liquid mass portion moving with the tank as an “impulsive” mass, and the sloshing effect on the surface by “convective” mass. Based on this research, several researchers have studied various aspects such as flexibility and the effect of axial forces on the tank wall, and the code parameters [8–10]. On the other hand, concerning the elevated silos with granular content, the entire structure and its contents behave like an inverted pendulum with a very large supported mass and the

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a. Elevated silos, Porto di Piombino, Italy

b. 10,000 ton steel grain storage, Australia [2]

c. SOC silos (ILVA) [3]

Fig. 1. Elevated silo examples.

weaker component under seismic action is usually the supporting frame. As the silo height increases, the height of the mass center also increases and the moment arm for the lateral load with corresponding overturning moment at the base rapidly rises. In this case, the behaviour of the stored material, and its properties, are usually less significant than in ground supported silos. Several modelling philosophies for the elevated silos have been compared in another paper [11], where it was concluded that concentrated mass approach provides sufficient degree of reliability to model elevated silos filled with granular content. Such approach has been also validated by several other researchers [12,13]. A more sophisticated method taking account of the interaction between silo wall and content would have a very large number of degrees of freedom, for which implementing an incremental dynamic analysis with several hundreds of accelerograms would not be feasible in terms of computational time and storage of the output data. Therefore, in this paper, the focus has been given on the seismic performance of supporting steel structure of the silo-group systems, which represents the main cause of their global collapse.

In many cases, the existing silos in the earthquake-prone areas have been constructed before the latest updates of the seismic design codes [3,11], hence their current seismic reliability is very low. After 2001 El Salvador earthquake, there were three causalities due to a silo collapse. After 1987 Edgecumbe (NZ) earthquake, steel milk silos collapsed, and thousands of liters of milk were lost. 1999 Chi-Chi Taiwan Earthquake caused collapse of silo because of the bottom segment and foundation anchorage, leaving the silo body without much damage [5]. After 7.2 magnitude Van (Turkey) earthquake in 2011, many industrial facilities with a lot of silos were seriously damaged, which caused a huge economic loss to the small and medium size companies because of both content and structure losses (Fig. 2). Almost all elevated cement and wheat silos were fully collapsed or seriously damaged during this earthquake [14]. After this event, main collapse modes were due to the rupture at the base due to excessive bending and bearing stresses, local buckling and anchorage failures, and welded connection failure [14,15]. These damages from the recent earthquakes highlight the vulnerability of elevated silos and the substantial need to find efficient retrofitting solutions to avoid the future disasters.

In general, seismic retrofitting of structures can be done in two ways: i) strengthening the structural elements to increase seismic resistance of the structure ii) using seismic isolation or dissipation devices to decouple the superstructure from the ground shaking effects. The first method is the traditional one, which requires often long construction schedules, and usually partial or full demolition and reconstruction that often leads to costly operations [16]. The second one has become quite popular and efficient in the mitigation of seismic effects on the building structures. Many successful applications have been reported [17–26], and their functionality has been validated under recent earthquake events [27,28].

Worldwide building codes mainly focus on civil structures. For industrial systems, the focus is given for the design of new structures, rather than the seismic rehabilitation of the existing ones. Isolation and dissipation devices have been largely investigated for civil structures, but there are not any specific indications for the application of these devices in the industrial systems. Some research has been done to study the effectiveness of the seismic isolation devices for the protection of ground-anchored tanks [29–32]. Elevated silos are treated in EN 1998-4-2006 “Silos, tanks and pipelines” [33], but without any provisions regarding seismic isolation.

Seismic protection of silos may be efficiently provided by the isolation devices. These devices reduce the seismic accelerations suffered by structures, shifting the first mode frequency to a low-energy range in the response spectrum [3,34] (Fig. 3). In this way, structure above the isolators does not get any damage from the earthquake, and its functionality is not interrupted for repair purposes [34]. After the earthquake, inspections and possible replacements are limited to the isolation devices, and not the bearing structure of the silos.

The European Research project PROINDUSTRY (Seismic Protection of Industrial Plants By Enhanced Steel Based Systems) aimed to develop innovative seismic protection systems, both for the design of new industrial plants and for the retrofit of existing ones, based on seismic isolation and energy dissipation techniques [3,12,13,35,36]. This paper presents the efficiency of curved surface sliders for an elevated silo structure studied in the PROINDUSTRY project. An existing elevated silo group located in Italy is selected as a case study. Its three-dimensional model has been developed using nonlinear plate elements for silos, and fiber-based distributed plasticity beam elements for structural components (all beams, columns and bracings). A total of 297 nonlinear dynamic time-history analyses have been performed, incremental dynamic analysis (IDA) [37] curves have been plotted for low-to-moderate