

Analysis of the structural integrity of a reinforced concrete building placed on regulating vessels

Abstract

The settlement of structures in low compressibility soils, in regulating vessels, has an impact on the degradation of structural integrity in reinforced concrete buildings, due to the severe seismic load; drastically altering the distribution of stresses, due to the inability of the structure to withstand seismic displacements, in response, structural failures of settlements, fissures, fractures, tension, bending, torsion occur, due to the loss of hypoplasticity. Furthermore, the depth of vertical displacement of the buildings seated in regulating vessels generates the dimensions of width and thickness of the cracks with incidences of fractures that are indications of unstable stresses, at which the structure was analyzed, presenting the critical level state collapse in structural disaster, due to high structural risk, causing loss of life and considerable material costs. This work is based on the Ansys methodology, for the analysis of the intensity of efforts and the rate of energy release, which generates the structural displacement of the building due to the action of seismic excitation, dissipating in seam due to the tensions and compressions to quantify the stochastic probability of severe risks of buildings displaced in regulatory vessels. Results show that the stochastic probability of disaster occurrence of buildings seated in regulatory vessels due to seismic action is 66.56 %, and it is also demonstrated that the displacement reinforcement is insufficient due to the energy release rate of the building.

Keywords: Risk, earthquake, fracture, stochastic, integrity

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Introduction

In ancient and modern times, several constructions, such as large monuments, towers, cathedrals; were built on soils not appropriate to their loads, representing causes of settlements in their supports being one of the most complex problems to solve, with loss of stability of the structure. In spite of the advances obtained in soil mechanics and structural engineering, these problems continue to persist, being the fracture of soils the most common cause of settlements in buildings due to the excess of load that it supports, causing the displacement of the structures; in tendencies to cracking and fissure in its structural elements. The filling of regulating vessels could cause damages, economic losses and in some cases loss of human lives, due to structural collapse by settlements. The collapse of a structure is the loss of capacity to support the gravitational action, as a response to the exhaustion of the resistance of the material; as what happened with the 2017 earthquake, which caused the collapse of 46 structures in Mexico City with 219 deaths; since these structures were deployed in artificially filled soils as a result of the urban development of the city.¹⁻⁷

Structural robustness and resilience has been demonstrated in the structures deployed in filled regulating vessels in the face of a catastrophic event, natural of an earthquake that has been inappropriate to set a minimum safety level of these constructions; due to the large deformations and the non-linearity of the materials as a consequence of the stresses exceeding their resistant capacity, which define the level of structural safety. There are insufficient studies of the constructions deployed in regulating vessels, where the performance of the structures predominates negatively and places the population in high danger due to the filling of the regulating vessels, of which its behavior before the seismic impact in the buildings constructed of reinforced concrete is complex. It is worth mentioning that the last seismic catastrophes have exposed their seismic vulnerability due to the deficiency of the design criteria and the construction

practices used. The seismic vulnerability of reinforced concrete constructions are exposed to the predisposition to suffer damage due to seismic occurrence; vulnerability is necessary for the knowledge of seismic risk and seismic disaster mitigation; seismic risk is the degree of expected loss suffered by structures during the period of the useful life of the structure that remains exposed to seismic action, usually the seismic capacity of a structure is estimated by non-linear static analysis; seismic disaster affects large populations producing social inequality.⁸⁻¹⁵ The objective of this work is to contribute and consolidate the knowledge of the structural integrity of reinforced concrete buildings, deployed in regulating vessels subject to seismic action and to know the structural fragility to avoid costly maintenance, in addition to their resistance and ductility of the structures.

Mathematical analysis of filled regulatory vessels

Clay coated regulating vessel

Flood control is a global and historically considered challenge. Development in flood areas increases economic damages and puts the health and safety of inhabitants at risk. The earth's structure has geographic contours that exhibit an innate center. In this innate center, rainfall has the effect of changing the environment, bringing about new conditions. The consequence of this pluvial precipitation triggers runoff from the elevated areas to the low areas; causing the formation of different volumes of water, such as streams and from these the rivers, with the diversity of conditions of the terrestrial area in the formation of lakes and lagoons; regulating the flow of water. This flow of water when passing over volumes of water to lakes and lagoons; causes abnegations; from which arises the need for the construction of the regulating vessel, as the catchment to contain and regulate the flow of water that by the orography of the valley are channeled naturally, otherwise it would cause enormous damage to the surroundings of human settlements. A regulating basin is a rainwater collector as an

essential drainage system, channeling them to prevent the abnegation of certain areas in times of rain, thus avoiding flooding, minimizing damage to businesses, homes and roads, Figure 1 shows the schematic shape of the regulating basin.¹⁶⁻¹⁹

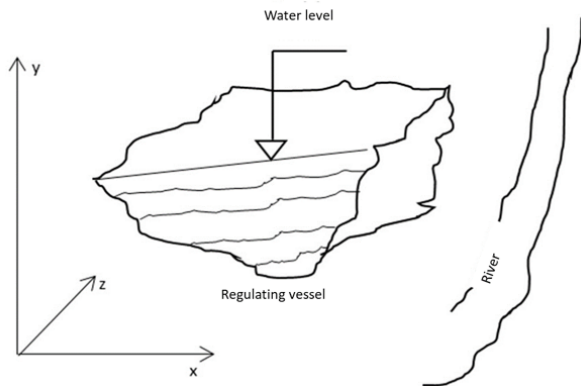


Figure 1 River regulating vessel.

Economic change in a region is very robust and has significant social and environmental consequences. As a result of these changes, there is an accelerated demographic and urban growth with the consequence of the expansion of the urban sprawl towards lands vulnerable to flooding, the emergence of areas of high socioeconomic marginality, invasion of private and public land by people looking for spaces to build houses or fill water bodies and buffer areas also called regulating vessels, which generates an atmosphere of tension and uncertainty among the population bordering the lagoon bodies, Figure 2 shows the erection of buildings as a solution to the demographic expansion of the population.²⁰

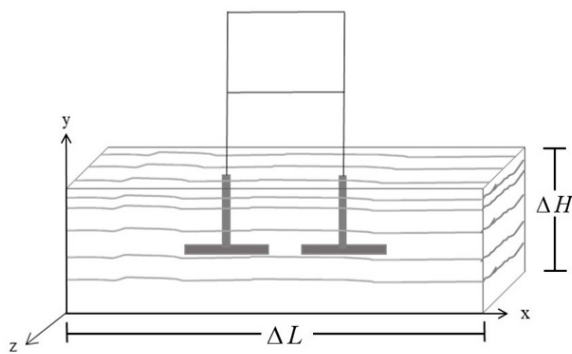


Figure 2 Regulating vessel filled to accommodate dwelling.

When filling a body of water, it is exposed to permeability, a term associated with the conductivity of the PM (Porous Medium) with respect to a fluid and indicates how easily a fluid flows through a porous medium. The complexity of the porous medium lies in the description of a medium where two very different materials coexist. On the one hand, there is a solid deformable matrix and on the other hand, the fluid that occupies the pores. According to Darcy the soil is a permeable material and is expressed by the following equation.

$$q = \frac{\partial V}{\partial t} = kiA \quad [1]$$

$$q = k \frac{\Delta H}{\Delta L} A \quad [2]$$

Where q is the flow rate per unit time, ∂V volume variation in a time differential, ∂t time differential, k is the permeability coefficient, i is the hydraulic gradient, A is the area of the section, ΔH increase in height of water rising, ΔL increase in length, see Figure 2.

Permeability in concrete is the exodus of water or other liquid element through the pores of the material in a defined time. The pores in concrete determine the environmental exposure of the material and damages coming from liquids, with more critical consequences to the corrosion of the constructive steel; in some cases, the condition of the concrete cooperates to the deterioration phenomenon, leading to structural restoration or replacement. Darcy's law shows the particularity of the displacement of the liquid through the pores.²¹⁻²⁴

Hypoplasticity

Volumetric changes induced in expansive clayey soils due to variations in their moisture content have resulted in significant structural damage. A reduction in the bearing capacity of the soil can cause expansion when the soil is saturated. The most susceptible soils may be normally consolidated clays and silts and certain types of saturated fills have generated significant structural damage; hypoplasticity, a theory created in 1977 by Dimitrios Kolymbas, explains the behavior of soil in a simple tensor relationship without requiring the elastoplastic theory to explain the same behavior of soil bearing capacity reduction. Hypoplasticity admits the occurrence of inelastic deformations from the beginning of the loading process. The parameters $\bar{h}$ and ϕ describe the stress-strain curves with constant strain rate. ϕ It reflects the compression curvature by the following equation.

$$\phi = \frac{\ln \left(\frac{e_1 \lambda_2}{e_2 \lambda_1} \right)}{\ln \left(\frac{p_{s2}}{p_{s1}} \right)} \quad [3]$$

Where e_i is the void ratio of loose material, e_2 void ratio with compacted material, λ_1 vertical displacement by loose material, λ_2 vertical displacement by compacted material, p_{s1} pressure load of loose material, p_{s2} pressure load of compacted material $\bar{h}_s$ (granular hardness) is the only constant that has a stress dimension (Figure 3), the following mathematical expression is shown.²⁴⁻²⁶

$$\bar{h}_s = 3p_s (\phi e / \lambda)^{1/\phi} \quad [4]$$

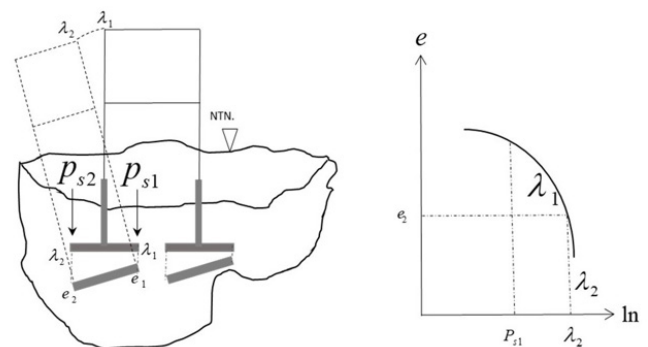


Figure 3 Compression of the foundation in a filled regulating vessel.

Settlement fracture

On the type of soil of the filled regulating vessel a structure is placed, it is possible that it suffers settlement due to the load that is added when expelling the water contained in the pores, as shown in

Figure 3; in addition, this type of soil has a very low permeability coefficient of the order of 10⁻⁷ cm/sec, the settlement occurs very slowly. Excessive settlements can cause damage to the structure, especially if the settlements occur rapidly, such as excessive bending compression and buckling of the reinforcing steel in the lower bed of the beams, inclination of the beams in the proximity of their ends due to diagonal tension with the appearance of cracks due to the inversion of the reinforcement, inclined cracking of the columns caused by diagonal tension (Figure 4,5).²⁷⁻²⁹

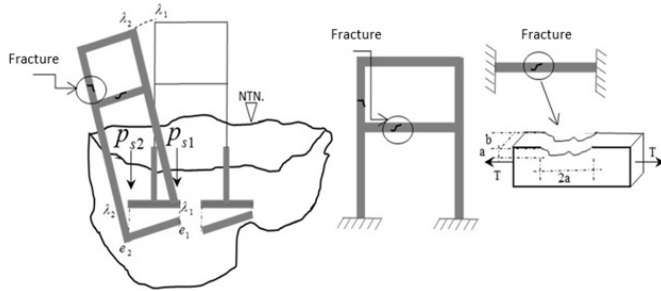


Figure 4 Diagonal settlement stress cracking in beams and columns.

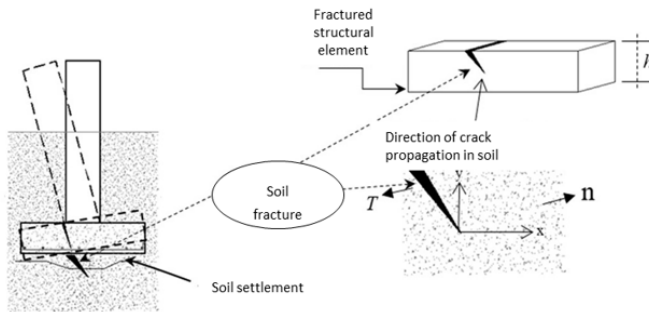


Figure 5 Proportion of soil fracture by settlement in the structural element.

Where T is the tensile stress of the crack contour, a is the depth of the crack, b is the thickness of the element, $2a$ is the length of the crack, ds is the length of the contour increment, n is the component of the unit normal vector and σ is the stress in the crack. In fracture mechanics, two methods of cracking are proposed; the energy criterion, which reveals the cracking which occurs when the energy available for crack growth is sufficient to overcome the strength of the material, and the stress intensity, which mentions that cracking occurs when the stress intensity factor is equal to or greater than the toughness of the material strength.^{30,31}

$$T = \sigma n \quad [5]$$

Structural integrity

Structural integrity is the part that studies structural safety in disaster prevention. Being the integrity of a structure, as the ability to carry out its functions effectively and efficiently in a defined period of time, without compromising the health, safety of its occupants and the environment; which comprises a wide range of disciplines such as: strength of materials, fracture mechanics, inspection techniques, repair of structural components, adaptable to industries such as power generation and transportation; referring to the evaluation of defects by non-destructive testing (NDE); facing the four main failure modes: fracture-plastic collapse, fatigue, creep and corrosion. The essential part of fracture mechanics is to define if the crack that appears in the structural element will remain stable or will be prolonged under

certain stress condition due to the load, with incidence in the integrity of the structural element. Figure 6 shows the fracture propagation by correlation of the soil fracture due to settlement in one of its supports by the filled regulating vessel, generating tensile stresses in the structural elements, whose structural mechanical properties lack the load capacity due to settlement, presenting fractures in its area and perimeter; the analysis of stresses in the crack tip is proposed as a plastic zone with a tendency to infinity, because part of the elastic energy is consumed in the plastic deformation of the material near the tip, regardless of the magnitude of the applied load (Figure 6).³²⁻³⁶

$$G = \frac{P_c^2 dc}{2b da} \quad [6]$$

$$C = \frac{\delta}{P} \quad [7]$$

$$\frac{\Delta C}{\Delta a} = \frac{C_2 - C_1}{a_2 - a_1} \quad [8]$$

$$G_c = \frac{K_I^2}{E} \quad [9]$$

$$E = \frac{E}{(1 - \nu^2)} \quad [10]$$

$$K_{IC} = \frac{G_c E}{(1 - \nu^2)} \quad [11]$$

$$\sigma_{xx} = \sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right) \left[1 \pm \sin\left(\frac{\theta}{2}\right) \sin\left(\frac{3\theta}{2}\right) \right] \quad [12]$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right) \sin\left(\frac{\theta}{2}\right) \cos\left(\frac{3\theta}{2}\right) \quad [13]$$

$$K_I = \frac{P}{b\sqrt{h}} \frac{3L}{2h} \sqrt{\frac{a}{h}} \left[\frac{1.99 - \frac{a}{h} \left(1 - \frac{a}{h}\right) \left(2.15 - 3.93 \frac{a}{h} + 2.7 \frac{a^2}{h^2}\right)}{\left(1 + 2 \frac{a}{h}\right) \left(1 - \frac{a}{h}\right)} \right] \quad [14]$$

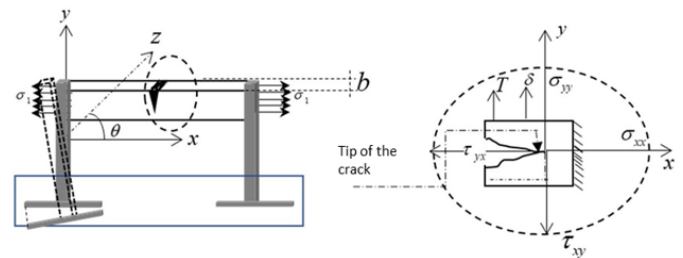


Figure 6 Fracture propagation by soil settling.

Where G_c is the energy release rate, E' is the plane strain elasticity of the material, ν Poisson's coefficient of the material, K_{IC} is the fracture toughness of the material in plane strain conditions, B is the thickness of the structural element, C is the elastic flexibility, P is the tensile load and δ is the displacement.³⁷⁻⁴⁰

Critical state of mild collapse

The strengths of structural elements are designed and analyzed to withstand seismic actions as a safety requirement, in columns or beams calculated to the limit, retaining their structural integrity and capacity to withstand residual load after the seismic event. The limit state of resistance prevents the possibility of collapse of the structure and the damage that can occur without endangering the lives of its occupants. Damage such as stress cracking in the structural elements settled in the backfilled regulating vessel, with the possibility of suffering settlement due to the load added by expelling the water content in the pores, generating instability and structural fragility in the event of any seismic event. Structural fragility is related to seismic vulnerability and can be quantified by means of fragility curves; and is defined as the representation of the cumulative distribution function, of the probability of obtaining or exceeding or exceeding the specific damage limit state, as a structural response to a seismic action.⁴¹⁻⁴⁴

$$P[ED \geq ED_i] = \Phi \left[\frac{1}{\beta_{ED}} \cdot \ln \left(\frac{Sd}{Sd_{ED}} \right) \right] \quad [15]$$

Where Sd_{ED} is the mean spectral shift for which the probability of exceedance is 50%. β_{ED} is the variability associated with the damage state, Φ it is the cumulative standard normal distribution function, Sd it is the spectral shift. ED It indicates the state of damage and is defined as: 1 for the state of slight damage, 2 for moderate, 3 for severe and 4 indicates the state of complete damage. The expected damage in a building depends on its capacity and fragility, although they are not independent concepts, they are closely related to each other.

Results

Table 1 shows the displacements due to seismic action, as well as the compressive and tensile stresses to which the structural elements of the building under study are subjected. It is worth mentioning that these tensile and compressive stresses are obtained from the complete simulation of the building.

Table 1 Tensile and compressive stresses due to seismic displacements in the building

σ_t (kg-cm ²)	σ_c (kg-cm ²)	CS (kg-cm ²)	t (min)	Δ (cm)	KI
28.852	-28.852	1,277.35	0.1	0.4791	0.33834688
21.656	-21.656	1,276.73	0.2	0.4631	0.4782464
21.655	-21.655	1,192.69	0.3	0.4471	0.58542617
21.655	-21.655	1,174.02	0.4	0.4312	0.67564189
21.655	-21.655	1,099.66	0.5	0.4152	0.75499993
21.655	-21.655	804.22	0.6	0.3992	0.82663377
21.654	-21.654	792.76	0.7	0.3833	0.89240586
21.653	-21.653	751.21	0.8	0.3673	0.95353037
21.653	-21.653	741.83	0.9	0.3513	1.01085114
21.653	-21.653	741.74	1.0	0.3354	1.06498289
21.653	-21.653	734.20	1.1	0.3194	1.11638997
21.652	-21.652	719.46	1.2	0.3034	1.16543331
21.652	-21.652	719.45	1.3	0.2874	1.21240011
18.872	-18.872	719.32	1.4	0.2715	1.25752337
18.823	-18.823	718.58	1.5	0.2555	1.30099522
17.887	-17.887	710.12	1.6	0.2395	1.34297632
17.736	-17.736	709.36	1.7	0.2236	1.38360265
17.654	-17.654	708.84	1.8	0.2076	1.42299052

The building under study, being subjected to stresses due to seismic action and specifically in regulating vessels, these have unstable tendencies in principle as shown in Figure 8, of which being housed the structure in the type of soft soil, there is a slight instability curve of which as the stresses increase, its displacement grows polynomially, as can be seen in the equation of compressive stress and the least squares in the range of 0.92 %, which in Figure 4 and 5, show the structural instability in this type of soft soil, which does not rule out the possibility of the appearance of cracks in the elements that degrade the structural integrity and therefore the risk of a possible structural disaster as shown in Figure 7, the plastic deformation of the structure in its structural buckling, as shown in Figure 9, the intensity of deformation and crack growth due to stress subsidence, this stress subsidence is the very representation of the stress intensity that guarantees the structural integrity as shown in Figure 10; However, this integrity is totally uncertain in these types of soil due to the porosity according to Darcy's law, as shown in Figure 10. As time goes by and the structure is exposed to seismic action, the resistance of the structural elements decreases until cracks appear because the structural elements that make up the building exceed their safety limit state as shown in Figure 11; The probabilistic tendency of slight collapse is in the order of 0.45 probability as shown in the bell; when the structure is subjected to the seismic force, a slight drastic impulse is observed that tends to grow from 0.66 impulse generated by its seismic spectrum as a structural response to seismic action, as shown in Figure 12. 66 of impulse that is generated by its seismic spectrum as a structural response to the seismic action, as shown in Figure 12, with the spectrum, slightly presents at the beginning a curve of the order of 1.8 which indicates that the structure is housed in an extremely unstable soil as shown in the structural seismic response due to its growing period with the lateral tension stress.

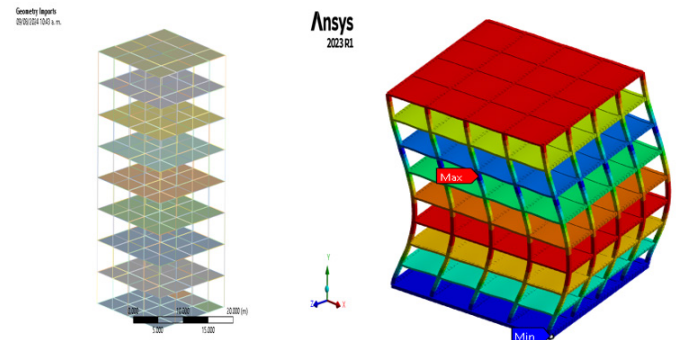


Figure 7 Building model generated by the ANSYS software.

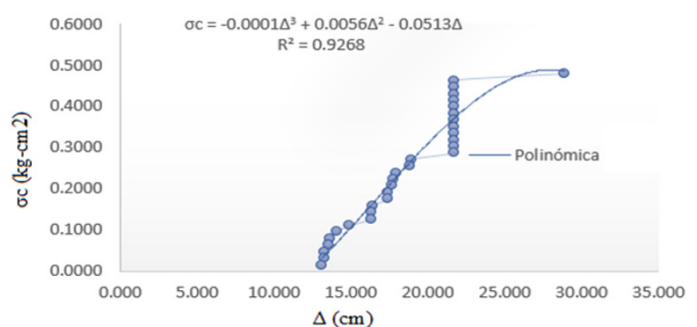


Figure 8 Deformation in structural elements.

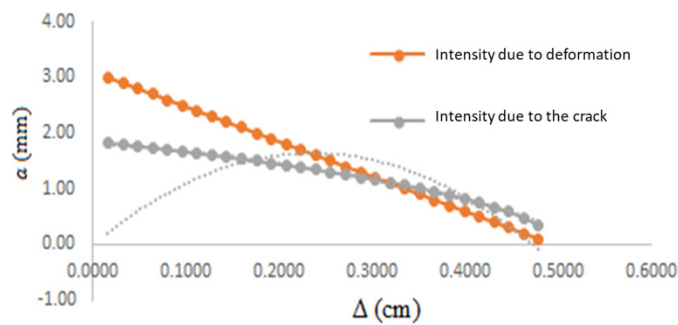


Figure 9 Cracking stress intensity.

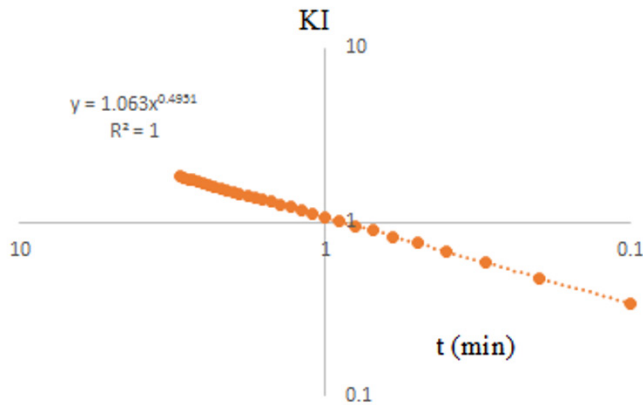


Figure 10 Time-varying seismic loading stress intensity.

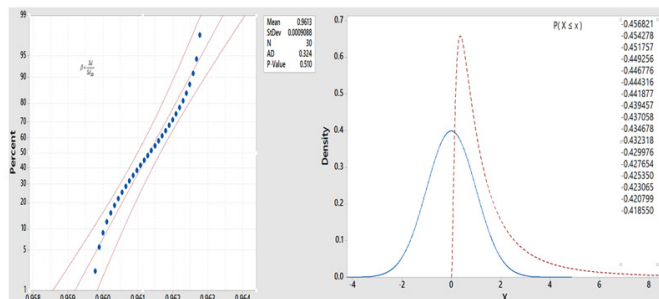


Figure 11 Structural safety response to seismic action in regulating vessel.

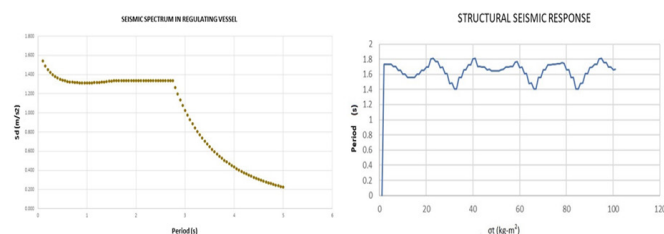


Figure 12 Structural seismic response in regulating vessels

Conclusion

It is concluded that the structural integrity of buildings that are deployed in regulating vessels are seriously in a critical state of risk with a tendency to disaster, as shown in Figure 7 and with a probability of failure presenting damages ranging from fissures, cracks, settlements of foundations, as shown in Figure 11, of which

a probability of failure of 66.56% is estimated in its elements, which could present sudden total collapse. This work is developed with the purpose of contributing and consolidating the knowledge of the structural integrity of reinforced concrete buildings deployed in regulating vessels; more research is necessary to strengthen and enrich the results that, among others, invite reflection.

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