DATE: 21/11/18

INTRODUCTION TO MALTA'S SEISMIC RISKS

A historical catalogue of felt earthquakes on the Maltese islands has been compiled dating back to 1530. Although no fatalities were officially recorded during this time as a direct consequence of earthquake effects, damage to buildings occurred several times.

However, it is to be stressed that historical knowledge of damaging earthquakes is sorely deficient. Not only is the information after 1530 incomplete, but damaging earthquakes before this date – though absent from the record – may be inferred to have affected the Islands. For example, the 1169 Sicilian earthquake had the same source, intensity at the source (I = XI) and probably a similar epicentral location as that of the 1693 earthquake, yet no records on of its impact on the Islands exist.

Out of the 100 events catalogued, 6 in number were damaging.The Islands lie in the middle of an extensive fault system affecting the central Mediterranean from Tunisia to Sicily. The faults, along which earth-quakes occur, are continuous through Malta and Gozo. Some of the faults are extinct, but others are young and still active. Malta, situated in the Sicily Channel, forms part of the relatively stable northernmost platform of the African continent.

Observations of recent earthquake activity around the Islands indicate, at first sight, a low level of activity, with small-magnitude events (<3.5) occurring at low rates. In the catalogue time period, the islands experienced EMS-98 intensity VII-VIII once (11 January 1693) and intensity VII, or VI-VII five times[1]. The occurrence of a magnitude 4.5 event close to Malta in 1972, together with the reported 1693 earthquake, shows the importance on outlining Malta's current Seismic Zoning. This may offer advice on the advantages for a particular building being made earthquake resistant or the advantages of retrofitting an existing building.

It is however to be noted that it is the large distant earthquakes, especially from eastern Sicily & the Aegean, with others only located within the Sicily Channel to the north of the Islands that have caused the most significant damage. It is further noted that it is not those generated either in the Sicily Channel or south of the Islands.

Eurocode 8[2] specifies that design ground acceleration on firm ground for a return period of 475 years has to be specified in the National Annex. The 475 year return period is based on the proviso that this ground motion is not to be exceeded in the assumed 50 years' design life of the structure in 90% of the cases.

[1] Galea P., Seismic history of the Maltese islands and considerations on seismic risk, ANNALS OF GEOPHYSICS, VOL. 50, N. 6, December 2007

[2] Eurocode 8. Design of structures for earthquake resistance. General rules, seismic actions and rules for Buildings: MSA EN 1998-1:2004

EARTHQUAKE FORCES

The energy dissipated by earthquakes is expressed in horizontal and vertical acceleration forces acting on the skyscrapers. The immense forces transmitted from underground must be absorbed by the supporting structures of the buildings. These dynamic loads are replaced by structural equivalent loads in horizontal and vertical direction when a structural analysis of the building is performed. The highest acceleration forces measured to date in an earthquake, were recorded during the Northridge earthquake in Los Angeles (17th January 1994) and amount to 2.3 times the acceleration due to gravity "g" ($g = 9.81m/s^2$) in horizontal direction and 1.7 times the acceleration due to gravity in vertical direction. In simplified terms, this means that the planning engineers would additionally have to apply roughly 2.3 times the dead weight in horizontal direction and roughly 1.7 times the dead weight in vertical direction to the building when dimensioning the supporting structure so that these earthquake forces can safely be absorbed. Fortunately as noted further down these seismic forces are noted to be much less for the Maltese Islands.

In simplified form, earthquake loads can be represented by horizontal and vertical equivalent loads acting on the mass centre of gravity of the building. The magnitude of these equivalent loads depends directly on the mass of the building. This leads to the conclusion that as the height of the building increases, the mass centre of gravity normally wanders upwards and the flexural effect on the building is intensified by the longer lever arm.

The far-field effects of large earthquakes are known to differ from those felt close to epicentres and whereas many types of buildings are effected in the latter locations, in the former, damage is more selective. During historic earthquakes, low- frequency structures (e.g., low rise complex buildings like cathedrals, large churches and palaces) suffered far greater damage from large distant earthquakes than high-frequency structures (e.g., stiff buildings such as low chapels and low rise houses with simple square or rectangular shapes). This is due to high frequency waves being more attenuated with increasing distance from a given epicenter than low frequency waves[3].

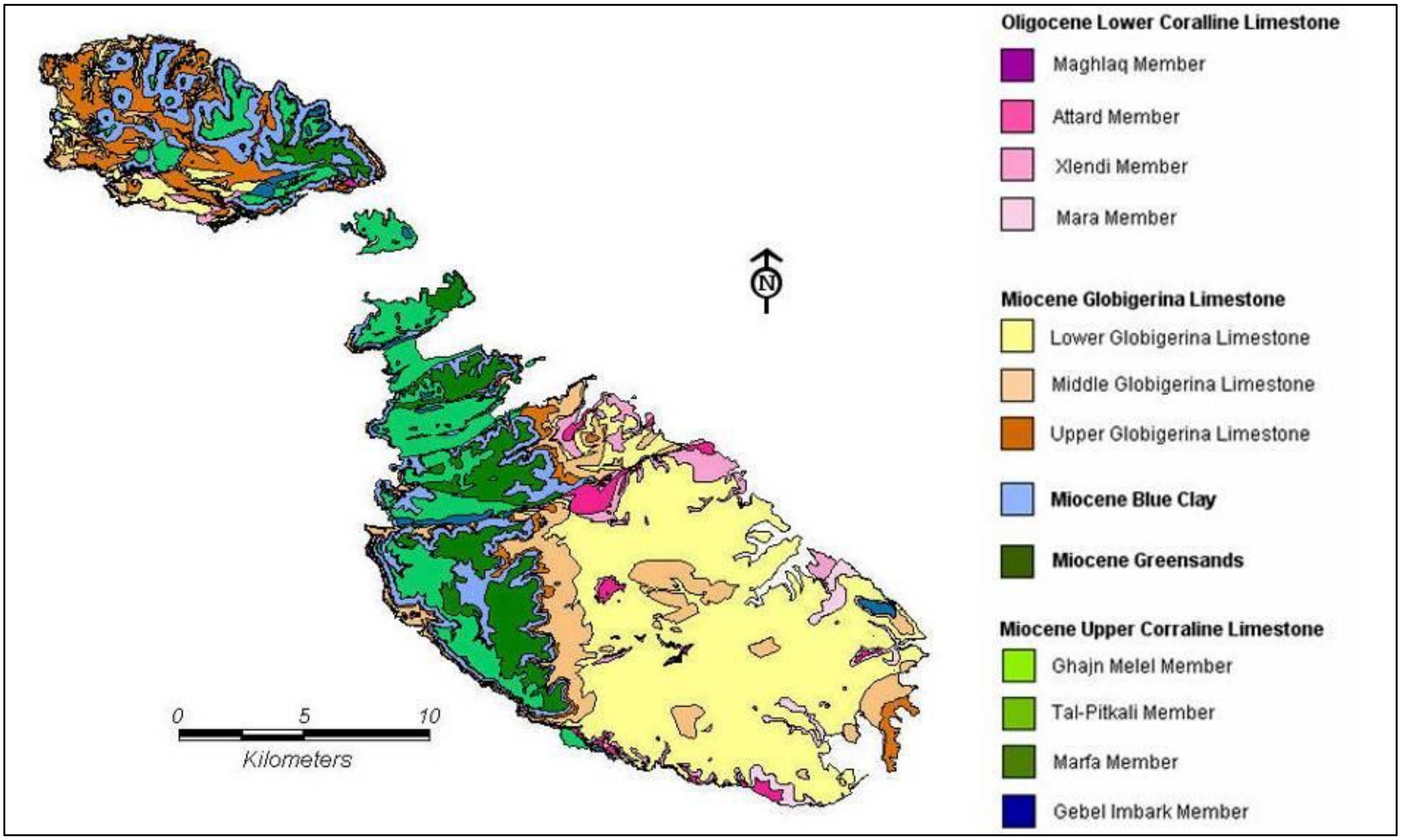
The most important and most serious effects are as outlined below, together with the possible protective measures.

[3] Main G. et alia, "The hazard of the Maltese Islands"' Nat Hazards, Nat Hazards, Springer 2018.

SUBSOIL

Natural rock is the best subsoil from the point of view of its earthquake properties. Sandy soils saturated with water and artificially backfilled land are considered to be particularly critical. The widely-feared liquefaction effects (plasticization of the soil) can occur if an earthquake coincides with high groundwater levels.

Figure 1: Geological Map of Malta (Source: https://goo.gl/P1c67p)



The other shades of colouring refer to different varieties of stable rock formations.

Fortunately most of Malta's buildings are founded on a stable limestone formation. Clay sites do exist limited to some areas in northern Malta and more frequent in Gozo. These may be located from figure 1, the geological maps as highlighted in light blue of the Maltese Islands attached.

The blue clay formation is a particularly problematic formation, as seismic waves are known to have triggered historic slope failures. Another problematic situation develops with blue clay cropping out below the upper coralline limestone. This causes instability of upper coralline limestone outcrops lying above the blue clay. Some rock spreads on plateau or sloping surfaces develop large limestone block slides. These however are locations where very few of Malta's building stock is located, with future buildings discouraged.

SUPPORTING BUILDING STRUCTURE

A distinction can generally be made between rigid and elastic supporting systems. Rigid systems, such as solid masonry wall and ceiling elements, are difficult to deform and transmit the seismic loads through their rigidity. Due to the stiffness and lack of ductility in the supporting structure, however, shear cracks can develop in the building. The problem is that more and more energy must be absorbed through the high rigidity and that more and more material is required for this purpose.

Elastic supporting structures, such as reinforced concrete or steel frames, are highly deformable and absorb the applied seismic energy in this way. The nodes connecting the horizontal and vertical elements of the supporting structure are highly stressed however, and peak loads occur both here and on the reinforcing elements (bonds) which must be taken into account when producing these connections.

The most common structural system adopted in Malta relates to cellular load-bearing masonry. A compact workable *franka* limestone building stone (crushing strength approx. 20N/mm^2) is an important natural resource. Terraced housing previously 2 or 3 stories high was considered robust and stable, but the needs of the motor-car, have introduced a soft open storey at ground or basement level. However with height relaxations ongoing over the past 15 years, these 2 – 3 storey buildings now account for 5 – 8 storey buildings in structural masonry.

The most economical structural system to span this 6 to 7m soft storey is by utilizing precast hollow prestressed slabs, with thicknesses varying from 230mm up to 525mm, supported on 230mm thick masonry laid in an M2 type mortar.

The concrete buildings constructed to date generally fall short of recommendations given by earthquake Codes for detailing methods of reinforcement, mostly in the tying of column-beam joint layouts and in the positioning of stirrups in beams and columns. Special care is also needed with prefabricated buildings, as their very design is often deficient as regards adequate interconnection.

SYMMETRY & SHAPE OF THE BUILDING

Symmetric layouts, rigidity and mass distribution lead to a considerably better seismic response than asymmetric layouts, rigidity and mass distribution. This is because asymmetric buildings are subjected to stronger torsion (twisting) around the vertical axis by horizontal seismic loads.

When parts of different height are permanently connect to one another as, for example, is often found in high-rise buildings with atriums, then the various structures in the building can be subjected to considerable torsional stresses by the seismic loads.

Resonance effects can also cause buildings to oscillate so strongly that they hammer against one another. Another effect observed in high-rise buildings is the soft-storey effect: due to lobbies, atriums or glazed shopping passages, some floors - usually near the ground floor – are distinctly “softer” than those above them. These “soft” floors then collapse in an earthquake.

CLASSIFICATION OF BUILDING TYPES FOUND IN MALTA

Rubble masonry buildings, as found in old buildings in Valletta or in the villages, being over 200 years old, are brittle. These buildings are made of stone set in earth, and such structures tend to fall apart even if shaking is moderate at MSK V.

The method depends on the 12" MSK intensity scale' which is roughly equivalent to the MM scale in actual values, varying as to degree of sophistication, including building types (Table 1), damage grades and quantities. The arrangement of the scale includes the effects on humans, natural objects, and the damage to buildings.

Table 1: Classification of Building according to anticipated Earthquake Intensity Damage

Type	**Description**	**Base shear design - % of gravity**
A	**Building of fieldstones, rubble masonry, adobe and clay**	**0.5%**
B	***Ordinary unreinforced brick buildings, buildings of concrete blocks, simple stone masonry and such buildings incorporating structural members of wood;***	***0.7%***
C	***Buildings with structural members of low-quality concrete and simple reinforcements with no allowance for earthquake forces, and wooden buildings, the strength of which has been noticeable affected by deterioration;***	***0.9%***
D_1	***Buildings with a frame (structural members) of reinforced concrete***	***2-3***

In Malta, a few buildings are classified as type B. These would be restricted to old, deteriorated rural dwellings exceeding 150 years in age or old, deteriorated buildings in Valletta in which, owing to little maintenance, stability has been impaired because of water ingress. Type A are limited to old, deteriorated rubble buildings, with age exceeding 200years, utilised as agricultural annexes. Most masonry buildings and most concrete frame buildings would be classified as conforming to type C. The more rigid buildings, satisfying stiffness regularity and symmetry in plan elevation layout, are classified D_l.

For buildings founded on softer material than limestone, the MDR* is taken as the progressively corresponding higher value on the scale: e.g. if a type C building, founded on clay, is subjected to MSK VI, its MDR* is to be based on an MDR of MSK VII, whilst if founded on a poorly backfilled, disused quarry, its MDR is to be based on MSK VIII.

* The mean damage ratio (MDR - Table 2) is the average damage to buildings of roughly similar vulnerability and architectural characteristics, expressed as a percentage of their new value.

Table 1 notes that the partially collapsed buildings in the 1693 event were classified as old and neglected, falling under Type A (5% PGA), on the other hand the buildings in Valletta suffering damage are classified as type B (7% PGA). At 7.5% PGA seismic activity the MM for this event falls between VII & VIII.

SEISMICITY & VULNERABILITY OF MASONRY CONSTRUCTIONS IN MALTA.

Eurocode 8 specifies that design ground acceleration on firm ground for a return period of 475 years has to be specified in the National Annex. The 475 year return period is based on the proviso that this ground motion is not to be exceeded in the assumed 50 years' design life of the structure in 90% of the cases for no collapse requirement. For damage limitation exceedance this is to be based on a 95 year return period, which signifies a 10% chance of exceedance.

It is recommended to consider as very low seismicity cases those in which the design ground acceleration on firm ground, a_g is not greater than 0,04 g (0,39 m/s^2). It is then recommended to consider as low seismicity cases those in which the design ground acceleration on firm ground, a_g, is not greater than 0,08 g (0,78 m/s^2). For very low seismicity the provisions of EN 1998 need not be observed. For low seismicity reduced or simplified seismic design procedures for certain types or categories of structures may be used. For all other design ground accerlerations > 0.08g, the recommendations of Eurocode 8 are to be abided by.

The worst recorded damage was during the 1693 event, which caused 60,000 deaths in Sicily. In Valletta it is reported that there was not one house that did not need some repair. The facades of some major buildings were detached from the main structure, and needed immediate repair. Some churches suffered major damage to their domes and severe cracks in walls. Serious damage was done to the old mediaeval city of Mdina. Here the Cathedral suffered partial collapse and many other buildings suffered serious damage. It should be noted that there are several remarks in the reports that show that many of the buildings in the city were very old and had been neglected for many years. In particular, the 13th century cathedral was already showing serious signs of disrepair before the earthquake, and plans had in fact already been drafted for its rebuilding. In Gozo, it was noted that the damage to the fortified Cittadella, was most probably due to long years of neglect, as was the damage to coastal towers.

Most of the houses were extremely shattered and deserted by the inhabitants who then lived in grottos and under tents in the fields. It is also mentioned that the Grand Master was hunting presumably in the Buskett-Girgenti area and was in great danger by the falling of a mountain near him. . Agius de Soldanis in his manuscript Gozo Antico & Moderno, recounts how the sea at Xlendi rolled out to about one mile and swept back a little later *"con grande impeto and mormorio"* in the earthquake of 1693[4].

Considering the above damage, rock falls in addition, together with a tsunami, it appears that intensity of the 1693 Earthquake works out at MSK VII - VIII. However, noting that no deaths have been recorded in the catalogues, it appears as from table 2, that this should tend closer to MSKVII.

[4] SHOWER, J. (1693): Practical reflections on the late earthquakes in Jamaica, England, Sicily, Malta, etc., London.

Table 2: Mean Damage Ratio (MDR) & Death Rates for building types B & C

Building Type	B		C	
Earthquake Intensity MM	MDR	Death Rate	MDR	Death Rate
5	2%	-	-	-
6	4%	-	1%	-
7	20%	0.03%	10%	-
8	45%	1%	25%	0.4%

Return periods may be identified from catalogues for earthquakes of intensity MMV & MMVI, whilst an MMVII/VIII was noted to have occurred only once, as in 1693, when a strong MMXI had hit the Eastern side of Sicily. Reference is also made to the the 1169 Sicilian earthquake noted in Introduction, with the same source and intensity at the source (I = XI). It is noted that an MMVII in Malta requires an MMXI in Sicily with a return period of 1,000 years.

Figure 2: Site seismic history for the Maltese islands since 1500, showing EMS-98 I ≥IV1[1].

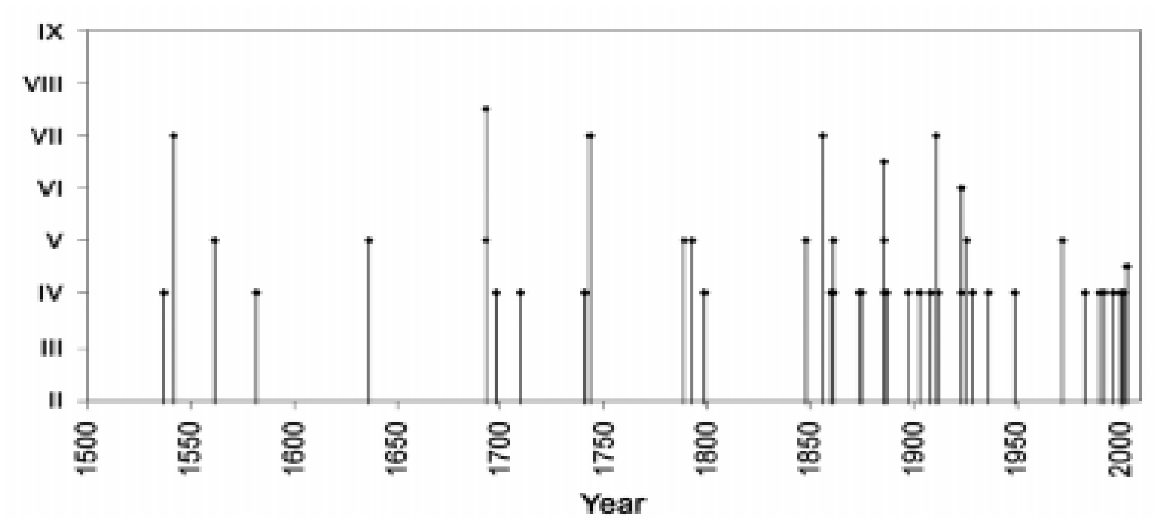


Table 3 proposes return periods in rock or firm soil for expected seismic activity in Malta for various earthquake intensities. These return periods have taken cognizant of historical data as per figure 2 and finally based on an educated guess.

Table 3: Malta's Seismic Return Period

MM – Earthquake	Return Period (years)	Base Shear Design
VI	125	2-5
VII	1000	5-10
VIII	10,000	10-20

From *Table 3* and plotting on a log-log graph, the 475 return period works out at 0.075g. This is also confirmed by the GSHAP – (Global Seismic Hazard Assessment project) map shown in *Figure 3* below.

Figure 3: GSHAP – (Global Seismic Hazard Assessment project) showing Malta

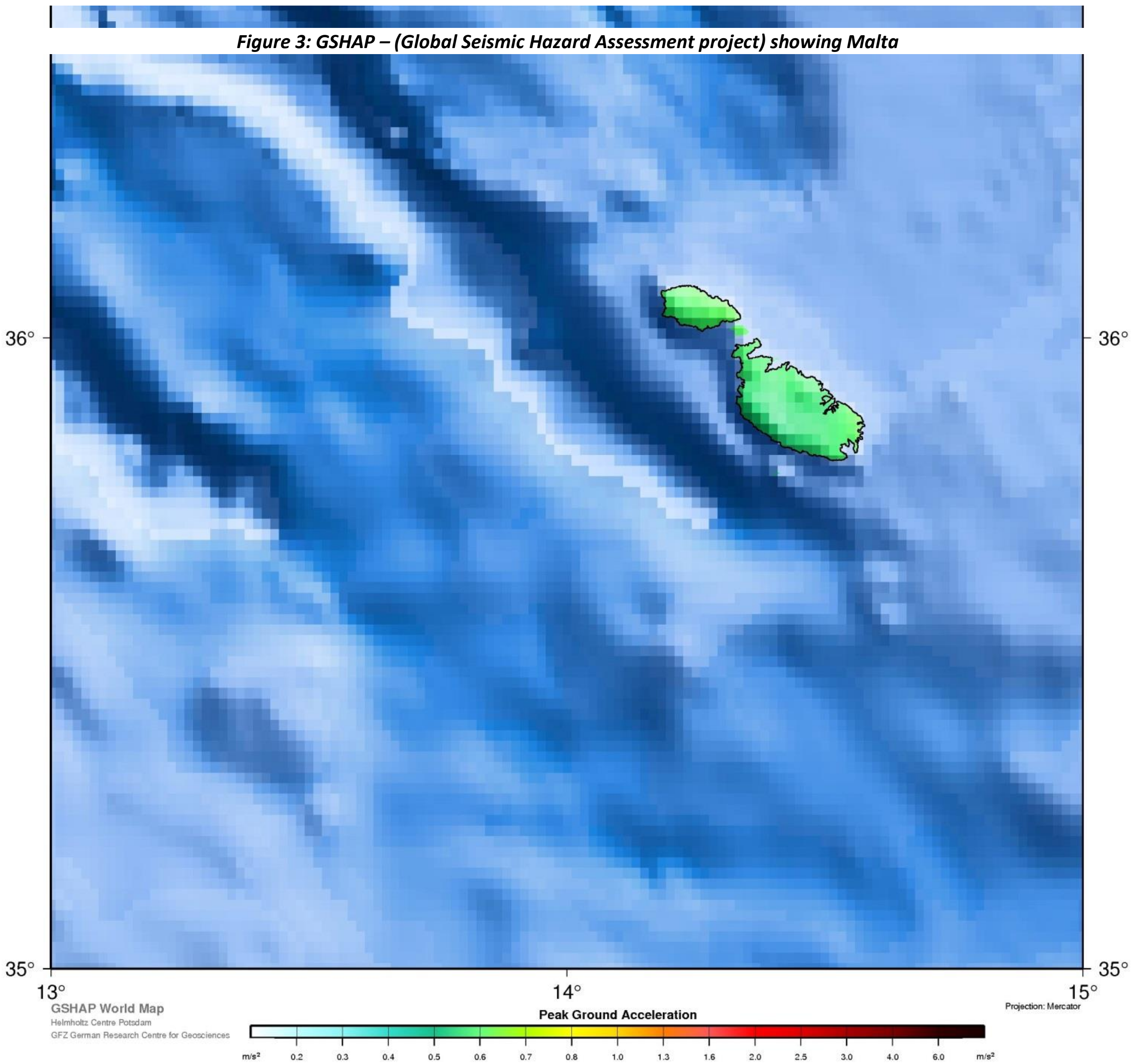


Figure 3 notes peak accelerations as varying from 0.7m/s^2 down to 0.55m/s^2, with the south eastern cliff face being the more stable location. The above ground acceleration values note the Maltese Islands according to EC8 to be classified for low seismicity.

Figure 4: GSHAP – (Global Seismic Hazard Assessment project) showing the Maltese Islands, Siciliy and Parts of Africa

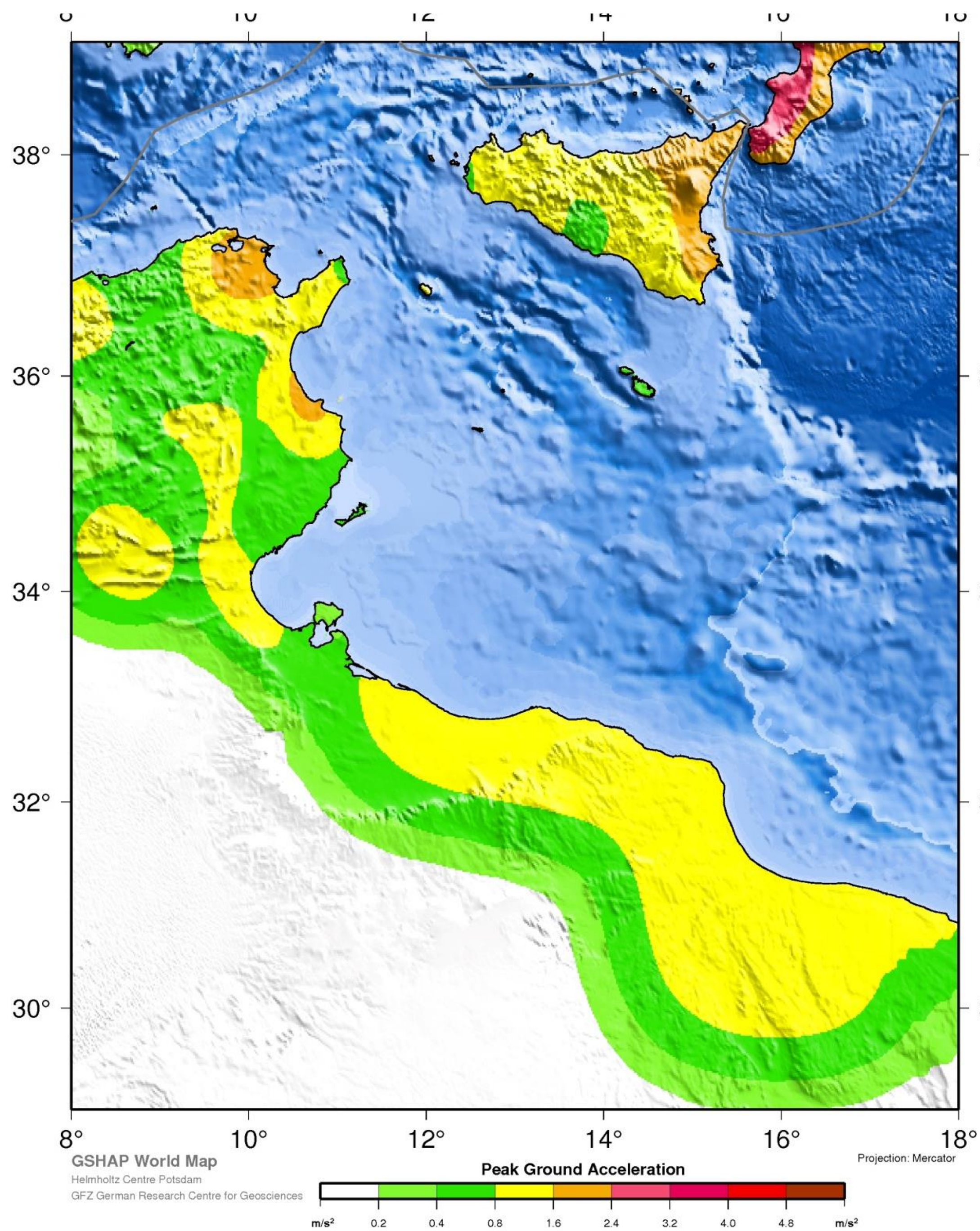


Figure 4 notes that the areas with a high seismic risk which are those noted with a brownish colour are: NE parts of Sicily (Syracusa, Catania, Messina) and parts of North Africa (Tunis, Ariana, Bizerta). The areas shaded in yellow have a lower seismic risk then the brown areas whilst the areas shown in light green have the lowest seismic risk. When compared to its surroundings, Malta has a low seismic risk as it is shown in green.

Munich Re further classifies Malta for seismic risk at zone 0. This defines the Maltese Islands as subjected to MMV & less, which according to the above may be noted as underestimating the seismic risk. Further studies note that according to the SHARE map and data, Malta is listed with PGA falling between 0.05g and 0.075g. This classifies Malta as a location with Low Seismic Hazard Risk, which agrees with above classification.

It is further noted that Malta's proximity to Sicily and its higher earthquake hazard have sparked in recent years a debate on the likely risk for the archipelago. A series of probabilistic seismic hazard assessment (PSHA) have been conducted and published in 2013[5] [6], showing results of PGA between 0.09-0.18 g for 10% probability in 50 years (475 return period), changing Malta's classification risk from "Low" to "Moderate". Notwithstanding this, the official seismic hazard classification for Malta remains "Low".

The above all converges to define the Maltese Islands as a low seismic area as per EC8, due to its design ground acceleration of 0.075g, falls within <0.08g but >0.04g, with simplified design provisions to be undertaken.

This is further confirmed as noted previously, that in the existing catalogue of Malta's seismic events, no mention is made of any deaths to have occurred. As further noted from table No. 2, the earthquake intensity should not have been higher than MMVII.

Further when historical evidence refers to houses being extremely shattered, these should be referring to very old constructions in rubble masonry, which as per table No. 1 are classified as type A constructions, which at a base shear design % of gravity at 0.5%, suffer damage to an MDR of 2% for MMV, 10% for MMVI, 45% for MMVII60% for MMVIII, as noted from table No. 4.

At this return period the earthquake horizontal effect on the building, is 2 ½ to 5 times higher than the forces imposed by the Malta design wind speed, thus confirming that seismic forces have to be taken into consideration in outlining the stability of high rise buildings for Malta.

Masonry EC8 Design Criteria for Zones of Low Seismicity.

EC8 notes the conditions under which unreinforced masonry that follows solely the provisions of EC 6[7], may be used in a country. It is to be noted that such use is recommended only in low seismicity cases. This implies that the normal masonry Eurocode 6 may be adopted for Malta.

1/- Shear walls in manufactured stone units are to have thickness t >175mm. **This fortunately is the thickness for internal partitioning adopted at 180mm.** For party walls due to acoustic considerations and for improved thermal capacity, a thickness of 230mm adopted.

[5] D'Amico, S., Galea, P., & Panzera, F. (2013). Seismic Hazard Maps for the Maltese Archipelago: Preliminary Results. American Geophysical Union.

[6] D'Amico, S., Panzera, F., Akinci, A., Galea, P., Agius, M., & Lombardo, G. (2015). Seismic hazard maps for the Maltese archipelago (Central Mediterranean). 26th IUGG General Assembly. Prague

[7] Eurocode 6 - Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures

Further h_{eff}/t <15
l/h_{min} < 0.35
where t is the thickness of the wall
h_{eff} effective height of the wall
h greater clear height of the openings adjacent to the wall
l length of the wall

2/-a minimum of two parallel walls is placed in two orthogonal directions. The cumulative length for each shear wall should be >30% of the length of the building. The length of wall in resisting shear is taken for that part that is in compression.

3/- For a design ground acceleration <0.07g, the allowed number of storeys above ground is 4 floors for unreinforced masonry and 5 for reinforced masonry, however for low seismicity a greater number of stories are allowed.

4/- Mortar type to be adopted should be at least M2, although lower resistance may even be allowed, whilst for reinforced masonry M4 may be used. Further there is no need to fill the perpendicular joints.

5/- Floor diaphragms may be considered rigid, if they consist of reinforced concrete. The connection between the floors and walls shall be adequately provided by steel ties at every floor level, spaced at not more than 4m centres, or reinforced concrete ring beams, reinforced with a minimum longitudinal reinforcement of $200mm^2$.

The Mean Damage Ratio (MDR) & the effects of Irregularity and asymmetry [8]

Table 4 is the average damage to buildings of about identical vulnerability and architectural characteristics, expressed as a percentage of their new value.

Table 4 - Mean Damage Ratio (MDR) For Building Type Against Earthquake Intensity founded on rock, being moderately asymmetrical & irregular[9].

BUILDING TYPE	**A**	**B**	**C**	**D_1**
EARTHQUAKE INTENSITY	MDR	MDR	MDR	MDR
V	4%	**2%**		
VI	10%	**4%**	**1%**	
VII	45%	**20%**	**10%**	**3%**
VIII	60%	**45%**	**25%**	**12%**
IX	80%	**60%**	**45%**	**30%**
X	100%	**80%**	**65%**	**55%**
XI	100%	**100%**	**100 %**	**85%**

[8] Camilleri D. H., Vulnerability of buildings in Malta to earthquake, volcano and tsunami hazard" The Structural Engineer Volume 77/No 22 36 November 1999.

The present majority range of Maltese buildings fall within types B-D_1 represented in bold in table 4.

For buildings founded on softer material than limestone, the **MDR** is taken as the progressively corresponding higher value on the scale. For example if a type C building founded on clay is subjected to MM-VI, its **MDR** is to be taken at 10%. Further, if founded on a poorly back-filled disused quarry, an **MDR** of 25% to be taken.

From table 4 it is noted that retrofitting a type C building from a type B would reduce the MDR at MMV, from 2% to nil, at MMVI from 4% to 1%, at MMVII from 20% to 10% and for a MMVIII from 45% to 25%. These damage savings may be achieved by modifying the method of construction and providing tying provisions.

It is recognised that an asymmetric or irregular design in buildings will suffer a higher mean damage ratio (MDR) than regular structures exposed to the same shaking.

A building may be slightly irregular or asymmetric due to the following factors:

- A small part is of different elevation
- The floor area is reduced from a certain storey upwards
- Elevator shafts or columns are asymmetrically arranged
- A part is of different stiffness

If a building has an "L"- shaped elevation or an "L"-shaped floor plan, or if foundations are resting on different sub-soil, the earthquake exposure is greater.

Elevations are easy to evaluate as regards asymmetry, but it is important to inspect all sides of a building. The inspection of floor plans should take all into consideration, as there could be major differences in plan between the ground and upper floors.

More difficult to assess are irregularities and asymmetries, associated with the internal properties of buildings, e.g. mass, stiffness or dampness.

An enhanced factor F_r shall be obtained for a highly irregular building, with abrupt change of stiffness between floors. The MDR's in table 6 are worked out for a weighting factor F_{r1} of 1.3 for irregularity and asymmetry in relation to a recessed elevation of building (shape A1 in table 5a) a similar value for F_{r2} (shape B1 in table 5b) of 1.3 in relation to an L-shaped floor plan whilst a value F_{r3} of 1.5 in relation to internal irregular spans and layout of walls of building (shape C1in table 8c) giving a global factor of:

$$\mathbf{F_{rA} = 1.3 \times 1.3 \times 1.5 = 2.5}$$

Table 5 -Amplification factor for anticipated damage to structures, depending on irregularity and asymmetry

(a) Irregularity and asymmetry effects on damage in relation to building elevation

Shape	Elevation	F_{r1}
A1	L-Shaped frame with increased height	1.3
A2	A soft structure introduced at ground level for majority of foot print area, overlying a rigid masonry structure above	4.0

(b) Irregularity and asymmetry effects on damage in relation to floor plan

Shape	Floor plan	F_{r2}
B1	A trapezoidal or L-shaped plan as opposed to rectangular	1.3
B2	A T-shaped plan	1.5
B3	A U-shaped plan	1.8

(c) Irregularity and asymmetry effects on damage in relation to internal features

Shape	Internal properties	F_{r3}
C1	Different spans of irregular arrangements of substantial internal walls	1.5
C2	Continuous window-bands interrupt fill-in wall, producing a short pier effect or substantial transitions in stiffness at ground level, due to large open spans	2.5

Soft designs encountered locally could incorporate a partial soft ground floor, yielding a F_{r1} factor of 4 (shape A2 in table 5a). A T-shaped floor plan with increased damage probability at both sides of intersection yields a F_{r2} factor of 1.5 (shape B2 in table 5b). For the continuous window bands at upper level yields a F_{r3} factor of 2. 5(shape C2 in table 5c), giving a global factor of:

F_{rB} = 4 X 1.5 X 2.5 = 15

The effects of asymmetry lead to an amplification of MDR given by

$$F_{rB} / F_{rA} = \frac{15}{2.5} = 6 \text{ times}$$

The local buildings which fall into this category are Buildings Type C, and D1 and an amended damage ratio matrix (table 6) is proposed to cater for higher asymmetry and irregularity.

Table 6 - Amended Damage Ratio Matrix for Higher Irregularity & Asymmetry

BUILDING TYPE	**C**	**D_1**
EARTHQUAKE INTENSITY		
V	10%	5%
VI	30%	18%
VII	60%	40%
VIII	100%	72%
IX	100%	95%

The absence of walls at ground floor implies a substantial transition in stiffness and some difference in mass and damping between the ground and upper floors. During the past 35 years the building construction in Malta has been subjected to changes, brought about from the economic expectations of landed property. The commercialization of buildings has opened up the layout especially at ground floor level, obtaining a flexible soft structure.

STRUCTURAL ROBUSTNESS[10]

This concept was introduced post 1968, following the Ronan Point gas explosion disaster that occurred in East London on the 16th May 1968. This concept has to form part & parcel of Malta's construction method in order to achieve lower MDR's, following a seismic occurrence.

Structural robustness involves structures that:

(1) don't fail like a house of cards;

(2) minor errors not to have a disproportionate effect;

(3) structures not to fail to any great degree under accidental loading

A building's structural form will significantly affect its robustness. Traditional cellular forms with many loadbearing walls assure a sensible level of robustness because loss of any one wall will generally not lead to the collapse of a large proportion of the structure. In contrast, having a large span supported on an easily dislodged and/or vulnerable single column would not be a robust structure.

Additionally, a robust structural concept will be one which avoids situations where damage to small areas or failure of any single element progresses to widespread collapse. Notwithstanding that ideal, there are clearly occasions when reliance does have to be placed on single elements, but at least once this is recognised, their robustness can be improved by making such elements substantial. Experience has shown certain arrangements to be potentially vulnerable; examples include:

[10] Mann A. P., et alia, *"Practical guide to structural robustness and disproportionate collapse in buildings",* The Institution of Structural Engineers, London, 2010.

– significant transfer beams, these are single beams which support a number of columns or hangers

– apparently minor elements that are required to ensure the stability of more significant elements

– significant cantilevers

– long span, simply supported beams*.

The last two forms have no redundancy but that need not imply unacceptable vulnerability.

Prescriptive rules for robustness include for the provision of horizontal ties both internal & peripheral for buildings up to 4 storeys in height. For buildings higher than 4 storeys, vertical ties are also to be provided for. On the other hand for buildings not higher than 4 floors instead of the horizontal tie requirements this may be supplanted by the provision of effective anchorage of the floors. Lack of anchorage would lead to instability in walls running parallel to floor spans. Most designers opt for providing effective floor anchorage to the walls/beams rather than specifying ties. Such anchorage can be achieved in most cases simply by the friction between the floor and the wall/beam although consideration of parameters such as temperature and camber may negate this approach. Where a floor unit is prestressed, its camber prevents proper contact with walls below running parallel to the span and so friction can only be relied on when bedding mortar is used.

Where in situ topping is not provided, reinforcement can be provided within plank end pockets with bars then grouted up to link units together.

CONCLUSIONS & RECOMMENDATIONS

From the above by classifying Malta's seismic risk hazard as low for the period under which a seismic catalogue has been drawn up, the same may not be same for the seismic vulnerability of Malta's building stock. It is further to be noted that the Eurocode National Annex could upgrade Malta's seismic hazard from low to moderate. Further it this possible that in the coming years, this will not remain a National Annex parameter.

EC8 threads carefully for masonry buildings above 4 stories heights for low seismic risk. For moderate seismic risk the number of load bearing masonry floors is reduced to 2. Increasing the classification to moderate seismic risk signifies that the majority of load bearing masonry buildings in Malta are not seismically resistant. Further the thickness of the shear walls noted in Cl. 8.10.1 will have to be increased to 240mm from the 180mm specified.

By comparing the base shear as a % of 'g' to be resisted in an earthquake of particular intensity from table 4, it is to be noted that for no damage to be suffered during an MMVI, building types to be D_1, and to higher specifications at MMVII & MMVIII. The above reinforces the fact quoted in codes that unreinforced masonry is disadvantageous against earthquakes, with types A to C buildings only resisting a nominal base shear. Consequently, it is not feasible with masonry construction to design an aseismic building above a certain level. It is recommended that reinforced blockwork construction, reinforced concrete or steel construction be used instead.

It has been noted that prior to the past 15-year period, Malta's height limitation had been limited to 2 to 3 storeys. In Valletta and Sliema buildings up to 5 stories high have been in existence over a long period of time. In Valletta 2 in number 8-storey buildings have been in existence for over 100 years.

Since 15 years ago the previous height limitations of 2 to 3 floors have gradually increased varying from 5 to 8 floors depending on location. Unfortunately these increased storey limitations have not been upped with improved construction methods. Unlike the high rise constructions presently being undertaken in Malta, which adopt a reinforced concrete cantilevered core construction around the stair/liftwells, these 5 to 8 floor constructions (in some locations even upped to 11 floors, considering the additional 2-floor hotel policy in place) still adopt the usual load bearing masonry constructions as undertaken in the previous 2 – 3 floors constructions. This all points towards, that whilst the Maltese Islands could be noted as a low seismic risk, the seismic vulnerability of buildings over the past 35 years in the medium rise masonry category of 5 to 8 floors heights together with additional basement floors has been increasing.

With the introduction of deep hollow core prestressed slabs in the early 80's, being utilized as transfer slabs, supporting a number of masonry overlying cellular residential floors, the incidence of soft storeys at ground floor was increased. These slabs, normally sit freely on the supporting structure, with no tying provided to the rest of the structural system.

Tying at corners for these medium rise buildings together with provisions for progressive collapse as outlined in EC1-7[11] Annex A, are not presently commonly undertaken. The tying of the various structural systems is a requisite to obtain a rigid diaphragm tying the whole building together.

On the other hand robustness requirements as issued post 1968 relate. These for all floor elements to be anchored to masonry walls so as to form effective horizontal ties in a similar manner to reinforced concrete structures: these are considered to have withstood the test of time in providing adequate robustness for masonry structures, which are not higher than 4/5 storeys.

Thus in masonry, it is usual to require the external walls and piers to be adequately connected to the floor construction to prevent their premature failure under outward pressure. This can be achieved by relying upon the shear strength of the connection, based on the type of masonry unit, mortar strength class and design vertical loading, or on its frictional resistance based on design vertical loading and appropriate coefficient of friction if the wall is loadbearing. This anchorage obtained in practice works instead of providing for the horizontal ties as stipulated.

[11] MSA EN 1991-1-7:2006, Actions on structures. General actions. Accidental actions