



Analysis of Dynamic Compaction Effects – Tavira Case Study

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Abstract. Ground vibrations are associated with different types of elastic waves propagating on the ground, and wave propagation depends on the soil stiffness, dumping and distance from the source. Urban activities also generate vibration, which are mainly associated to traffic of heavy vehicles, railway compositions, infrastructures construction, and maintenance. On site construction, ground wave propagation occurs when pile driving, dynamic compaction, blasting, and operation of heavy construction equipment is required. Regarding vibration energy analysis in structures, the Peak Particle Velocity (PPV) is the reference parameter and according to the Portuguese standard NP 2074 (2004), “Evaluation of the vibration impact on buildings, caused by explosions or similar construction procedures”, the PPV can range from 5 mm/s up to 20 mm/s, for rigid structures founded, respectively, on sandy soils and soft clays, or rocks and hard clays. The study hereby presented is a real case study where the effect of heavy vibratory tandem compaction, associated to the construction of an industrial parking in the vicinity, caused extensive wall cracks on a reinforced concrete structure, located 60 m from the site construction. The structure is an unifamilial building, located on the northern urban area limit of Tavira city, in the Algarve, Portugal.

Keywords: Ground vibrations · Vibratory compaction · Structure’s damage

1 Introduction

Ground vibrations are associated with different types of elastic waves (i.e., bulk, shear, and superficial waves) propagating on the ground. Wave propagation depends on the soil stiffness, dumping, and distance from the source [1].

Artificial vibratory energy from urban activities generates waves in the frequency range of 1 Hz to 150 Hz, whilst for natural vibration sources, such as earthquakes, the predominant energy transport is associated with waves of the frequency between 0.1 Hz and 30 Hz, and for the wind load effect in tall buildings, it is from 0.1 Hz to 2 Hz [2]. The common sources of vibration in urban areas are mainly the traffic of heavy vehicles, railway compositions (trains and undergrounds), infrastructures construction, and maintenance. The main sources of ground vibrations associated to site construction are pile driving, dynamic compaction, blasting, and operation of heavy construction equipment. These vibrations may harmfully affect surrounding buildings, and their effect

ranges from disturbance on residents, aesthetical cracks on walls to visible structural damage. They are usually felt by the habitants, leading to discomfort on users, due to slab, windows or doors movements, lamps displacements, as well as vibration of object inside cabinets.

The waves are propagated by the superficial soil/rock layer and primarily received by the building foundation, inducing a displacement on it, which, in turn, will be transmitted to the structure. The response of the building to this excitation depends on the natural frequencies of the structure, its modes of vibration, and damping [2]. If the resonance frequency of the building structure is similar to the frequency of propagation of the vibratory wave, there will be an amplification of soil/foundation displacement, causing an unwanted impact.

For rigid structures founded on medium to soft soils, the walls displacements are neglectable due to the stiff structure response at lower frequencies. For flexible structures founded on stiff soils and rocks, the soil-structure displacements at the interface are low, however the structure will transmit the vibration, and consequently cracks may occur on masonry walls [3]. In this last case, the wave frequency has high impact on the lower dumping building components (walls, ceilings, modular lining, divisions), since they have higher natural frequencies and therefore are more influenced by the continuous vibrations (fatigue) [4].

Regarding vibration energy analysis in structures, the Peak Particle Velocity (PPV) is the parameter used to measure it. According to the Dutch standard DIN 4150-3, there are three building categories, and they can support different limit levels of PPV [5]. For steel or reinforced concrete structures, they tend to have better responses to vibration effects. Nevertheless, even with small PPV, these structures can suffer damage when founded on stiff soils, as mentioned earlier. The Portuguese standard NP 2074, "Evaluation of the vibration impact on buildings, caused by explosions or similar construction procedures", define PPV limits according to the soil foundation, structure type, and constructive typology [6]. For conventional structure, the PPV can range from 5 mm/s for sandy soils and soft clays up to 20 mm/s for rocks and hard clays. The difference vibratory wave velocity in different types of soils is associated to the elastic impedance of each one.

2 Case Study Description

The study hereby presented is a real case study where the effect of heavy vibratory tandem compaction was felt on an unifamilial building, causing vibration on the reinforced concrete structure (RCS) and extensive wall cracks. During the compaction works the residents captured, on video, lamps bouncing on ceilings, dishes vibrating inside cupboards, and doors moving. The compaction works were associated to the construction of an industrial fruit packaging and distribution park, located 60 m from the unifamilial building. The site construction parking place, for the compaction equipment's, was only 41 m away (Fig. 1).



Fig. 1. Distances from the damaged unifamilial building to the industrial park under construction and to the compaction equipment's parking place (Goggle Earth aerial image, taken on February 2020).

The compactions works were interrupted immediately after the alarm, being followed by an assessment of the structure pathologies and by the project revision. The characteristics of the compaction equipment's, as well as the structure, local geology, lithology, and geotechnical characterization were fundamental for the comprehension of the phenomena.

2.1 Unifamilial Building Characterization

The building is a three-floor house, composed of a basement, ground floor, and 1st floor, built in 2007, and with 304.90 m^2 of constructed area.

The building is a reinforced concrete structure, founded on shallow foundations and with stiff concrete walls on the basement contour. The superstructure consists of columns, beams, and massive slabs. The concrete and steel characteristics are: C16/20 for foundations; C20/25 for all the others concrete elements (slabs, beams, pillars, and walls); S400 in all structural elements.

Considering the information gathered on the Housing data sheet, the surrounding exterior walls have a thickness of 33 cm and are composed of two cloths of 11 cm bored brick masonry. In between, there is an air box, partially filled with 30 mm thick thermal insulation wall mat, fixed on the interior cloth. All façade walls are lined outwardly by plastering and inwardly by designed stucco. The hillside walls are simple of perforated brick with a total thickness of 25 cm, coated inside with projected stucco. All interior walls consist of simple cloths of 11 cm bored brick masonry, coated with designed stucco, except for the kitchen and sanitary facilities where ceramic tile was applied.

According to the proprietary, the exterior walls were repainted on 2015/2016 and the interior between May to July of 2018.

2.2 Geographical Location and Geomorphological Landscape

The structure is located on the northern limit of Tavira city urban area, in the Algarve, Portugal (Fig. 2).



Fig. 2. Geographical placement of the unifamilial building in the Algarve region (source: Google Earth, 2022).

The city extends from the south coastline, bathed by the Atlantic Ocean, known as “Litoral”, to the northern smooth hills, designated as “Barrocal”. Algarve’s morphology is a mixture of different landscape. The “Serra” region is characterized by steep slopes with rounded hills and dispersed rocky outcrops. “Barrocal” as a slightly rugged landscape, similar to “Serra”, and the hills are covered by Mediterranean vegetation, forming a unique landscape. Regarding the “Litoral” coastline, the Western part is characterized by rocky cliffs and the Eastern part by sandy dunes, islands, and long beaches (Fig. 3).



Fig. 3. Algarve region geographical division: “Litoral” = coastline, “Barrocal” = in between zone, “Serra” = mountains (source: [7]).

2.3 Geological and Lithological Site Characterization

Algarve is a complex Mesozoic sedimentary basin. The most recent formations (Jurassic, Cretaceous, Miocene, Pleistocene, Pliocene and Holocene) are located in the South and Southeast, whilst the oldest formation (Paleozoic) is on the West and North of the Algarve (Fig. 4). Algarve's lithology is also very rich. The sandstones, conglomerates, and sands, associated to sedimentary formations, are the dominant type of rock massifs along the “Litoral” coastline. Clay shales and graywacke prevail on the “Serra”, however, an igneous formation intrusion, constituted by nepheline syenite rocks, is the “Serra de Monchique” birthplace. “Barrocal”, the in-between zone, is mainly constituted by limestones, sand stones, and dolomites (Fig. 5).

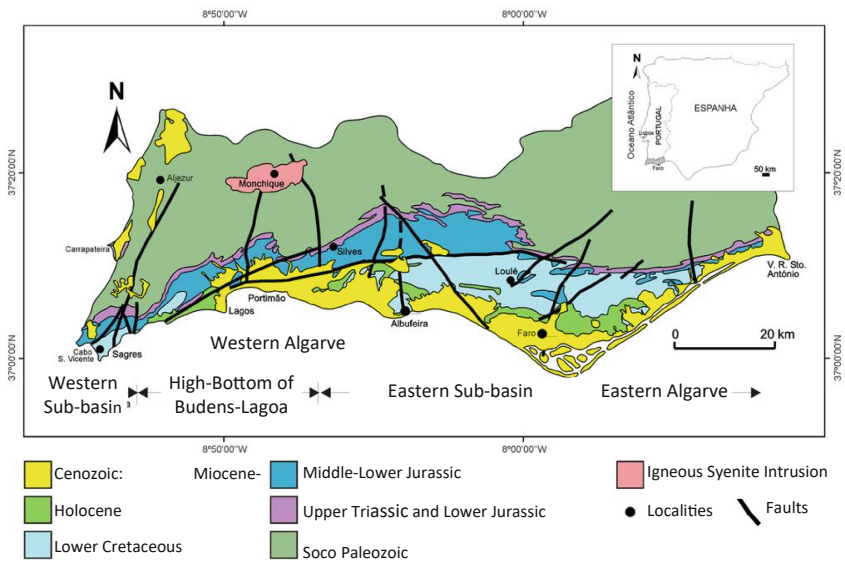


Fig. 4. Simplified geological map of Algarve (source: [8], based upon [9]).

The unifamilial structure is on the fringe of “Litoral” and “Barrocal”, where conglomerates, sandstones, clayey sandstones, limestones usually dolomitic, marls and marly limestones from the Upper Triassic-Lower Jurassic, and dolerites from the Middle-Lower Jurassic are the predominant formations. In this specific zone, the massif is relatively close to the soil surface, and rocky outcrops are common.

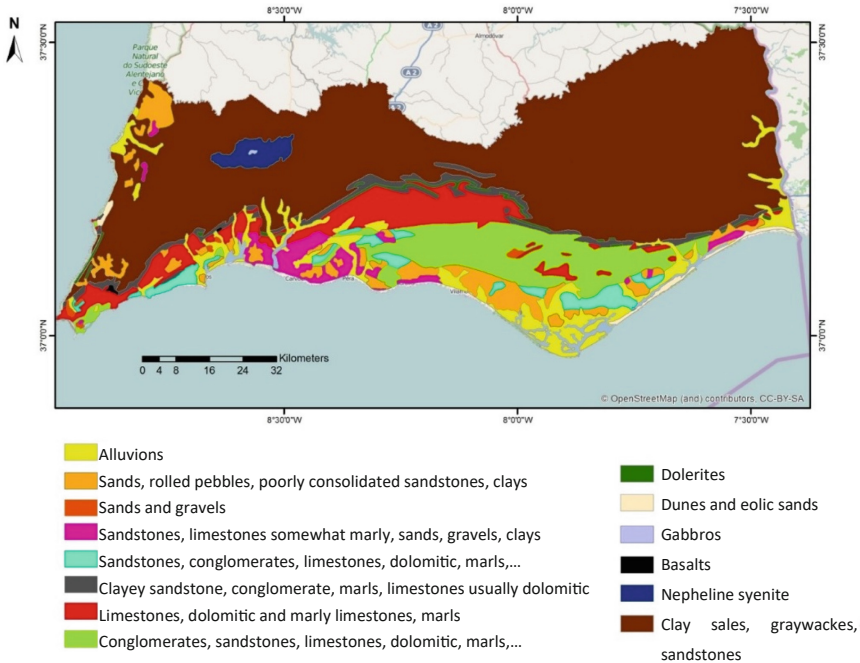


Fig. 5. Algarve lithological map (source: [8], adapted from [10]).

2.4 Pavement Characterization and Compaction

The pavement of the loading/unloading parking zone was not considered on the initial design project, and therefore, this was an additional work. The pavement characteristics adopted were proposed by the contractors and defined after visual inspection of the soil foundation, after scarification. Fragments of rocks were detected on the soil surface and no “in-situ” tests were performed.

The pavement characteristics prescribe were:

1. Granular sub-base with variable thickness, aiming to level the parking pavement.
2. Well grade base, preferably *tout-venant*, with 30 cm (15 cm + 15 cm).
3. Asphalt layer, in bituminous material, with 10 cm.

After compaction the sub-base and base course materials must met the following criteria:

1. At least 95% of the Modified Proctor test.
2. The layers must be perfectly stable.

Additional criteria:

1. Moisture: A uniform distribution of water must be carried out, using pressure whose jet tanks, if possible, in order to cover the total width of the compacted area. The water spreading should be continuous and maintaining the same speed, however soil saturation cannot occur. If case of excessive moisture, compaction works must be delay, giving time for the material to dry.
2. The upper surface layer should present a uniform texture, free of cracks, undulations or loose material and may not, at any point, present differences greater than 2.5 cm in relation to the longitudinal and transverse profiles established.
3. The total thickness of the sub-base, after compaction, must respect the valor prescribe. If the projected thickness is not attended, then scarification and correction will be executed. However, if supervisors agree, the compensation thickness of sub-base layer can be added to the base layer and increase its thickness.

A motor leveling machine or other similar equipment was used for the spreading of the material. Spreading will be done regularly to warranting a perfectly homogeneous layer. If sulcus, wheel ridges or other inconvenient marks were perceptible on the layer surface, and correction of the deformations are imposed.

2.5 Compaction Equipment and Procedure

Due to heavy raining on the beginning of the compaction works, the *tout-venant* already applied had to be completely removed, since it showed high water content. It was also remarked excessive percentage of fine particles on the aggregates – therefore, it was rejected. After this incident only “first category” *tout-venant* was used on compaction.

The first compaction equipment choice falls within a heavy vibratory single drum smooth roller – ABG Alpha 190V cylinder with an operating weight of 11 ton and frequencies ranging from 30 Hz to 35 Hz [11] (Fig. 6a).

However, after the heavy vibration effects, felt on the surroundings, the contractor opted for a light tandem smooth roller – Ammann ARX36 with an operating weight of 4ton and frequencies ranging from 41 Hz to 55 Hz [12] (Fig. 6b). The vibrations reduced significantly, but the number of cylinder passages necessary to ensure the compaction criteria increased, taking more time.



a)



b)

Fig. 6. Images of the compaction equipment: a) vibratory single drum smooth roller, b) vibratory tandem smooth roller.

2.6 Non-structural Pathologies

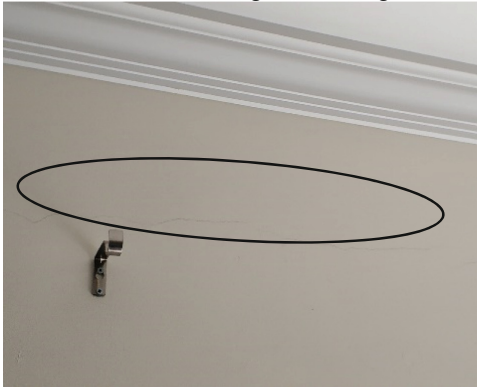
A technical assessment was carried out to determine the extension of the damages on the building, affected by the vibrations, and no structural anomalies were founded. However, extensive non-structural pathologies were easily perceptible and visible, especially on the wall coverings and ceilings, both exterior (Fig. 7a, b) and interior (Fig. 7c, d).



a) Joint displacement with implication to other elements of the contiguous dwelling.



b) Cracking on the balcony wall.



c) Cracks on the living room near the ceiling.



d) Tiles from the bathroom fractured.

Fig. 7. Images reporting visible cracking of the exterior and interior covering walls.

3 Proposed Solution

Since the causes of the pathologies on the unifamilial building were caused by the compactions works, they were immediately interrupted after the alarm, followed by the decision of contacting an expertise team, to advised them on the type of compaction machinery to use and for the building repairing.

3.1 Compaction Equipment Proposed

The major implications of using a vibrator compaction equipment on the vicinity of this urban area, where the upper soil is rather stiff, is the vibration propagation. In the case study, the effect on the structure building was amplified due to its stiffness. A rigid reinforced concrete structure will vibrate as a part of the ground itself and the basement moves along with the ground, passing the waves to the above structure [13].

The solution to minimize the vibrations passed by choosing a static tandem roller or an oscillation compaction equipment. This last one was considered the most adequate. Oscillation works by using exciters to move the drum back and forward, rather than directing the forces downwards as a conventional drum. This effect is achieved by having twin, coupled out of balance exciters synchronized, that rotate at the same speed but in opposite directions [14] (Fig. 8).

The direction of the forces is a key issue for oscillation since they act horizontally and generate shear forces. These causes the soil to move both downwards due to the weight (load) applied, but also laterally. So, the drum remains in contact with the layer surface, delivering both dynamic as well as static loads to squeeze out any voids. The aggregates are redistributed within the mat, instead of being damaged and this avoids the risk of over-compaction.

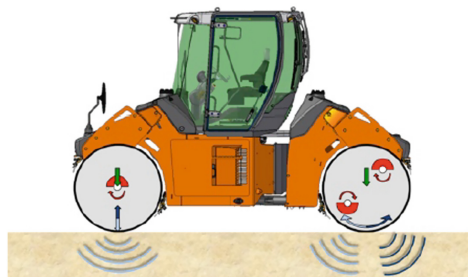


Fig. 8. Forces and moments of dynamic drums: vibrating drum (left), oscillating drum (right). (source: [14]).

A crucial advantage associated to this type of compaction is the 85% reduction of vibration, to obtain the same compaction effect. By comparison, when using conventional vibration techniques, the out of balance (up and down) weights act only vertically, and these forces can be reflected off underlying layers, travelling some distance through the ground. In urban areas, this can be of concern as it may affect surface structures of all types in the vicinity.

Both soil and asphalt compactors are available with oscillating type drums in the market, but the technology is of particular benefit for asphalt applications, and therefore its common to only find them being used by pavements contractors. The oscillating compaction method can be used effectively for base, binder and wearing courses.

3.2 Walls Repairing Solution and Procedure

Regarding the interior wall coverings repair, it was proposed the replacement of the cracked ceramic elements, as well as the ceiling/crown molding, followed by a complete painting. For the external elements, a slimy armed mortar was prescribed. However, the criteria requests for waterproofing, permeability to water vapor, support compatibility, and durability had to be taken into consideration when choosing the coating. The repairing procedure for the affected regions, was:

1. Pressure water washing to remove non-adherent paint, dirt, and other contaminants. Surfaces should be dry and without residues of aged paints afterwards.
2. Treatment of fungi with Antibiosis Decontaminant, N/Ref. 18-220, and wait 24 h before painting.
3. Plastering, with proper mortar, the bigger cracks, and for the smaller ones application of "Tapa cracks, N/Ref. 18-110".
4. Application of Primary Cynolite HP, N/Ref. 10-850 on the repaired areas.
5. Application of a general fiber mortar Princol, N/Ref. 29-573.
6. Application of a sandy mortar, N/Ref. 29-575, for plaster regularization. The painting should only be done after 10 to 12 days after the mortar.
7. Application of a primary layer of painting Cinolite HP, N/Ref. 10-850.
8. Application of two to three coats of Novatex HD, N/Ref. 10-175.

4 Final Considerations

Intense vibrations were video recorded once the compaction works of an industrial fruit packaging and distribution park started. Windows vibrating, doors and lamps movements, as well as dishes vibration inside cabinets (equivalent to a seismic phenomenon) were registered and observed for several days by the owner of the unifamilial affected building.

The equipment, initially used for the parking sub-base and base aggregates compaction, could be considered adequate and efficient for the purpose if the rocky substrate was not so close to the surface. Also, the compaction roller drums frequencies were within the range of values usually used in this type of soil. This parameter is not the most determinant in the compaction effect, but it is for vibrations propagation. Thus, given the proximity to other structures built in the area, it can be stated that the initial compaction equipment was not the most appropriate, having transmitted the vibration into the rocky substrate, which were subsequently transmitted to the building foundations and superstructure.

The major influence on compaction is the value of the wave amplitude (Peak Particle Velocity) transmitted by the equipment. Unfortunately, this parameter was not measured

during the compaction works and consequently no comparison to the maximum PPV standards could be made.

Despite the significant pathologies observed on the wall's coatings, ceiling mouldings and tiles, especially on the ground floor divisions, no structural pathologies were found after the expertise assessment. The cracks on the exterior and interior walls are extensive and some present a considerable dimension. The repair works had to be carried out immediately and a slimy armed coated was prescribed.

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