

Behaviour of wedge foundations under axial compression

A Ciutina¹, M Mirea¹, A Ciopec¹, V Ungureanu^{2,3}, R Buzatu¹ and R Morovan¹

¹ CCTFC Department, Politehnica University of Timisoara, 1A Ioan Curea, 300224, Timisoara, Romania

² CMMC Department, Politehnica University of Timisoara, 1 Ioan Curea, 300224, Timisoara, Romania

³ Laboratory of Steel Structures, Romanian Academy, Timisoara Branch, 24 Mihai Viteazu, 300223, Timisoara, Romania

Abstract. Wedge or tapered foundations of buildings, which have greater top cross-sections than bottom ones, are not often considered as a design option due to their shape. However, precast wedge foundations could be considered as “quick foundation systems” in case of light structures which should be rapidly installed. Similar to tapered piles, this foundation shape can offer besides the bottom base resistance, a good lateral contact between the inclined concrete faces and the surrounding soil. The paper presents the experimental results of two wedge foundation specimens subjected to axial compression tests conducted in accordance to actual standards. The results recorded on sites are presented under the form of pressure-settlement diagrams and are compared with similar values recorded for usual prismatic foundations. The study is completed by an environmental impact analysis made on the two systems along with potential benefits and loads, beyond the system boundary, at the foundations’ end-of-life.

1. Introduction

In case of emergency following calamities the fast installation of intervention units is an imperious requirement. The emergency units are usually realized by transportable units as containers and are installed on single or two storeys. The structures do not transmit important loads to soils and need pinned supporting at the base. In these conditions, the time required for the execution of foundations sets the laying of the objective.

The precast foundation units could be quick installed in place, thus are surnamed quick foundation system. In order to minimise the overall weight of foundations and ease of handling, the foundation units could be made by tapered faces, in the form of a frustum, similar to foundations executed in punched holes. Unlike the regular prismatic foundations that produce important base pressures and valueless friction on lateral faces, wedge foundations improve the bearing capacity of the base pressure by an important gain due to inclined faces. These produce additional friction with the foundation soil, similar to the foundation piles with variable section.

Wedge foundations have been traditionally studied in the context of punched foundations and the design formulae for bearing capacity integrates the strength of improved soil with/without the gain of the granulated material bulb. The additional bearing capacity due to inclined faces could be added by evaluating the friction between soil and concrete [1]. Various studies investigated the design formulae for independent foundation units – elbows – or connected by a top raft, in order to deduce the design formulation of the elbow-improved foundation soil system bearing capacity [2].

On the other hand, various studies performed on variable section piles demonstrated that the face inclination leads to a net increase of the bearing capacity, which extends with the inclination angle. This phenomenon is due to the interaction between the lateral faces and the surrounding soil [3-5].

Considering the sustainable built environment, a prefabricated foundation unit presents a series of advantages over the cast-in place units: it could be re-used as is the case of temporary structures and be easily handled at the End-of-Life.

Based on an initial experimental investigation on precast wedge foundation, the paper presents additional FEM models and existing design formulae that could be applied to such systems. The study is completed by an environmental impact analysis, proving the beneficial character of the precast units.

2. Experimental and Numerical Investigation on Precast Wedge Foundations

2.1 Description of specimens

The foundation solution for a two-storey 5x5m lightweight steel-framed module consists in using precast wedge foundations inserted in dug holes.

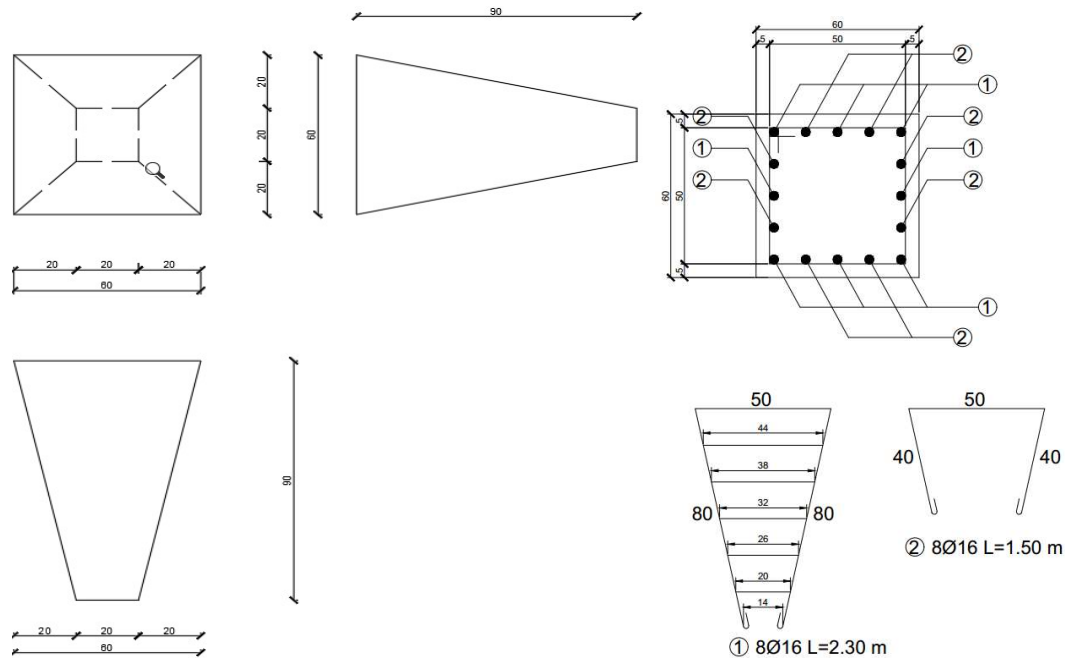


Figure 1. Dimensions of the precast wedge foundations.

The dimensions of the foundations are presented in Fig. 1. Considering their shape, the foundations are of intermediate height, having $h/b_{med} > 2$. The foundation soil was investigated through a boring report, as well as laboratory testing for the determination of physical-mechanical properties. The boring was made up to a depth of -4.00m. Thus, there have been identified three soil layers with different physical-mechanical properties:

- under the vegetal soil was identified a layer of brown hard silty clay (-0.30m to -0.70m);
- between -0.70m and -1.40m a layer of stiff brown silty sandy clay;
- below -1.40m, the soil is a stiff black silty sandy clay.

The foundations were installed in holes, dug larger than the foundation with 5-10 cm on each lateral side. The interlocking between the foundations with the concrete foundation was made with cement-mortar, cast after positioning of the foundation unit. Thus, it could be the final dimensions of the foundations is bigger than the nominal one.

2.2 Experimental testing

The experimental tests were done by static axial loading on two identical wedge foundation specimens, as described in section 2.1. The axial vertical loading was applied by means of a hydraulic jack with an axial force capacity of 450kN, acting against a ballasting frame (see Fig. 2a). The load and the settlement were automatically monitored through a data acquisition system (Fig. 2b). The settlement was recorded

in four points on the top face of the foundation, by means of four transducers fixed on an independent frame.

The foundation solution for a two-storey 5x5m lightweight steel-framed module consists in using precast wedge foundations inserted in dug holes.

The static load was applied in force steps of 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165 kN, equivalent to soil pressures of an equivalent median foundation area from 41 kPa to 458 kPa. The loading steps were maintained up to stabilization of settlement, the mean settling time for one load step being 2 hours. The stabilization of the settlement was considered as reached when the settlement increment recorded in 20 minutes was smaller than 0.1mm, according to NP 045-2000 [6].



Figure 2. Ballasting of the foundation F1 (a); Loading system and data acquisition (F2) – (b).

2.3 Experimental results: load-settlement curves

The results recorded on the two wedge foundation specimens are presented in terms of load-settlement response curves (Fig. 3a). It is to be stressed that due to the special form of the specimens, it was decided to represent the curves as force settlement instead of the usual representation pressure-settlement. The envelope curves were plot by joining the corresponding settlement settling points at increasing loading steps. Although the response of the two specimens is similar in the domain of linear behaviour – up to a force of 60kN, in the non-linear domain the two specimens have different behaviour. Thus, the behaviour of the specimen F2 is more rigid than F1, as noticed in Fig 3b. The behaviour difference is due basically to two reasons: (i) non-homogeneity of the soil – the specimens were installed at a distance of 10 m and (2) the final shape of the specimens after casting the interlocking cement mortar. The latter was visible after testing and extraction of specimens from the ground.

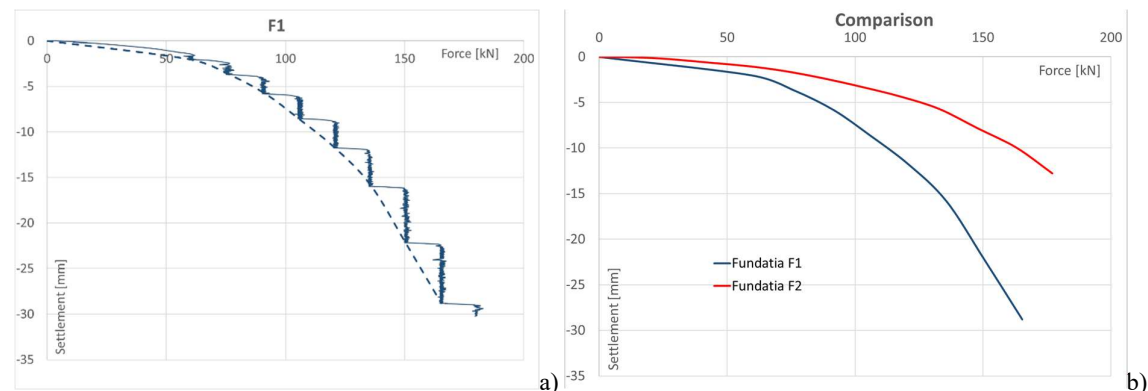


Figure 3. Load-settlement response curve (specimen F1): real response curves and envelope (a); Comparison of load-settlement responses, specimens F1 and F2. (b).

2.4 Bearing capacity of wedge foundations

At the recovery of foundations from the soil it was observed a non-uniform increase of the transversal section on height (see Fig. 4) due to the interlocking cement mortar stuck on the precast foundation. Due to this reason, in order to consider in a realistic way the modified form of the foundation in design and FE modelling, the original dimensions of the foundations were increased by 5cm on each side, thus considering a modified geometry having the same height (90cm) but increased dimensions of the top face to 70x70cm and respectively bottom face to 30x30cm.



Figure 4. Shape of foundations before and after testing.

According to NP 112 [5], the bearing capacity of the foundation could be estimated according to formula (1). However, this formula is applied to the general prismatic shape with non-tapered lateral faces. For this reason, for the design of the wedge-shaped foundation it was considered the reduced area of the foundation A' , given by the average area of the foundation of 50x50cm.

$$R_d = A' (c'_d N_c b_c s_c i_c + q' N_q b_q s_q i_q + 0,5 \gamma' B' N_\gamma b_\gamma s_\gamma i_\gamma) = 132.1 \text{ kN} \quad (1)$$

where:

$c'_d = 23 \text{ kPa}$ is the design value of the effective cohesion

N_c, N_q, N_γ non-dimensional bearing capacity factors taken as: $N_c = 13.06$; $N_q = 5.24$; $N_\gamma = 1.34$

b_c, b_q, b_γ non-dimensional factors for the inclination of the foundation base, taken as $b_c = b_q = b_\gamma = 1.0$

s_c, s_q, s_γ non-dimensional factors considering the shape of the foundation, taken as: $s_c = 1.38$; $s_q = 1.31$; $s_\gamma = 1.38$

i_c, i_q, i_γ non-dimensional factors considering the inclination of the vertical force V due to the horizontal load H , taken as: $i_c = i_q = i_\gamma = 1.0$

$q' = 15.9 \text{ kPa}$ natural soil pressure at the level of the foundation basis,

$\gamma' = 17.9 \text{ kN/m}^3$ mean volume weight of soil layers

The resulting value of the bearing capacity of 132 kN of the foundation allows the computation of a critical pressure $p_{cr} = 528 \text{ kPa}$, value considered as consistent for a foundation realised in a silty-clay soil.

For the estimation of the bearing capacity of a foundation with tapered faces which allows differential the estimation of bearing capacities on the basis and respectively on the lateral faces, an out of use norm was used: *Design and execution guide for punched holes for foundations*, code [1]. According to this document, the bearing capacity of the foundations cast in intermediate (punched) holes is determined as the sum of the forces transmitted on the basis and the forces transmitted by friction through the lateral faces of the foundation. As in the analysed case the soil was not improved, the compaction effect of the ground around the foundation unit was taken as unity:

$$P = k m (A R_v + Q_f) = 81.6 \text{ kN} + 65.3 \text{ kN} = 146.9 \text{ kN} \quad (2)$$

where:

$k = 0.7$ - non-homogeneity coefficient

$m = 0,7$ – working conditions coefficient

A - bottom section of the foundation unit ($0.3 \times 0.3 \text{ m}^2$)

R_v – soil resistance at foundation base level: $R_v = \alpha_v R_p$

α_v – coefficient considering the type of the foundation soil = 0.5 for clays

R_p – is the thrusting resistance of the penetrometer tip in the foundation soil, taken as 3.7 MPa for stiff-rich clays

Q_f – is the critic load corresponding to the bearing capacity to lateral friction:

$$Q_f = U_{med} h \alpha_l R_p / \alpha_s \quad (3)$$

with $\alpha_l = 1.0$ – coefficient considering the compaction effect (usual 1.25)

α_s – coefficient considering the type of soil $\alpha_s = 50$ for clays

$U_{med} = 4 \times 0.5\text{m}$ - mean-height perimeter of the transversal section of the foundation

h – foundation height (0.9m)

Although the bearing capacity of the foundation unit computed according to the in-use standard (132 kN) and respectively the out of use guide (146 kN) lead to comparable values, some differences exist between the two approaches:

- due to the fact that the NP 112 norm cannot consider the foundations with tapered faces, the bearing capacity of the foundation unit was considered on the basis of a constant-base prism, having the basis of square shape with the side equal to the mean side of the analysed wedge foundation;
- the C230-89 design guide makes a distinction between the transmission of vertical by basis pressure and respectively friction on the lateral faces. However, the design resistance on the lateral surface do not depend on the tapering angle of the faces but only on the soil layer depth and the type of soil;

According to the values computed by the formula (2), the value of the bearing capacity on the foundation basis (81.6kN) is greater than the bearing capacity due to friction and wedging on the lateral faces (65.3kN).

3. FEM Investigation

To have an insight distribution of internal forces and to observe the deformations of the surrounding soil zone, a FEM analysis was realised by using the computer code MIDAS GTX [7].

3.1 Model description

The base model used in FEM analysis integrates a wedge concrete foundation unit, in a 3D space that models the foundation soil. The geometric dimensions used for the FE models were the considering the original dimensions (see §2.1) increased by 10 cm on horizontal sides in order to consider the interlocking mortar. Thus, a torus was obtained having the top base of 0.7x0.7m, the bottom base of 0.3x0.3m with a height of 0.9m. The dimension of the soil solid was of 6x6m.

Two characteristic materials were used for concrete and soil ground, characterized through:

- concrete: elastic-plastic model, considering the strength $f_c = 16 \text{ N/mm}^2$ and the modulus of elasticity $E_{cm} = 29000 \text{ N/mm}^2$. The compressive resistance was evaluated on compressive cubic samples at 28 days;
- foundation soil, considered as a single layer having the following average characteristics: Linear modulus $E = 20000 \text{ kPa}$, cohesion $c = 23 \text{ kPa}$, internal friction angle $\Phi = 18^\circ$. The material model adopted in analyses was of Mohr-Coulomb type.

The contact between the foundation soil and the concrete foundation unit was modelled by “interface” contact element type, considering a friction coefficient $\mu = 0.35$. The lateral and bottom faces of the soil solid were blocked to deform out-of-plane. In contrast, the top soil surface was free to deform. Both the soil solid and the foundation unit had a finer mesh in the central part – the maximum mesh dimension was 10cm and gradually increased to the edges where the mesh dimension was of 60 cm. Fig. 5 presents the foundation and respectively the soil solid mesh.

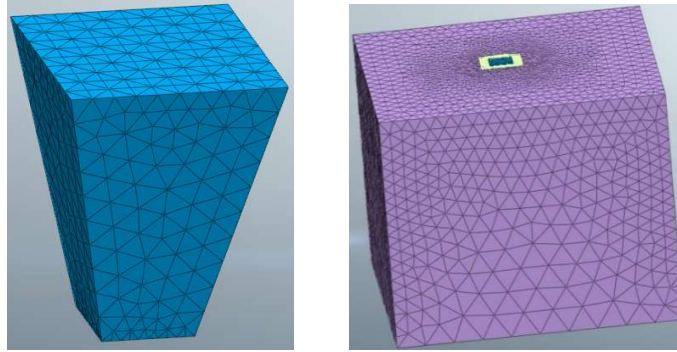


Figure 5. Meshing of foundation elements – a); Meshing of the foundation soil, including the wedge foundations – b).

3.2 Calibration of results

Considering the variability of the foundation soil that lead to different responses of specimens F1 and respectively F2, the numeric response presented as load-settlement curve in Fig. 6 is considered as calibration of experimental response. This response was obtained by using the soil characteristics presented in section §3.1.

Fig. 7 presents the deformed shape of the soil solid and the Von Misses equivalent stresses. As expected, the maximum stresses are recorded at the foundation base and on the lateral faces of the concrete unit.

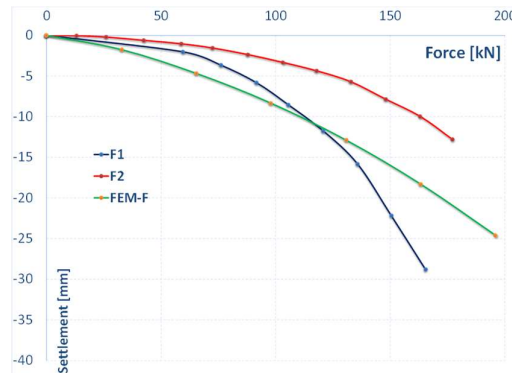


Figure 6. FEM calibration curve vs. experimental results.

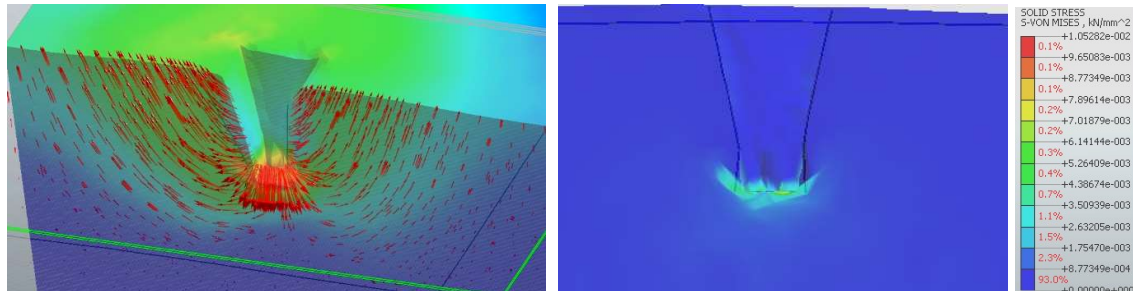


Figure 7. Deformed shape of the foundation soil / Von Mises stresses -final loading step.

3.3 Contribution of lateral faces to the total bearing capacity

In order to check the contribution of lateral tapered faces to the bearing capacity of a wedge foundation unit, supplementary FE models have been created:

- the original model of the wedge foundation unit, denoted as FEM-F;

- the model of a foundation unit (denoted as FEM-5), having an orthogonal prismatic shape and the basis of 50x50cm and the height of 90cm. The purpose of this model was to check if the response of a regular foundation unit having the base equal to the average section of the wedge foundation is similar to the response of the foundation with tapered lateral faces;
- the model of a foundation unit (denoted as FEM-3NF), having an orthogonal prismatic shape and the basis of 30x30cm. This model has defined friction conditions only at the inferior basis while the lateral faces although in contact with soil do not develop shear stresses. FEM-3NF model was created for evaluation of the force developed by the original foundation units (FEM-F);
- the model of a foundation unit (denoted as FEM-3), having an orthogonal prismatic shape and the basis of 30x30cm and identical friction conditions on the base and lateral faces. The model was developed for the evaluation of the share of forces brought by the lateral faces (in direct comparison to the model FEM-3NF).

For all the models presented above, similar material characteristics, boundary conditions, contact, friction (exception of model FEM-3NF which develop friction on the bottom face) and respectively meshing were considered as presented in section §3.1.

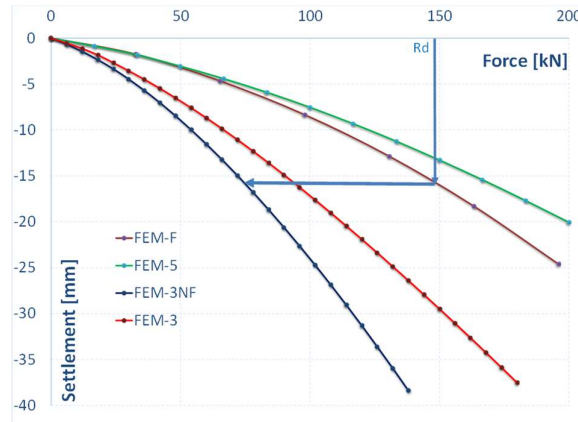


Figure 8. Comparative results of FEM models.

Fig. 8 presents the results of the numerical simulations under the form of characteristic curves Force-settlement. The obtained numerical results one could draw the following conclusions:

- the behaviour of the model having the average section (FEM-5) is similar to that of the behaviour of the original wedge model (FEM-F). However, the differences in behaviour increase for higher compressive forces and the design on equivalent prismatic foundation became non-safe;
- for a settlement of 16mm, the bearing capacity resulted for the model FEM-5 is of 170kN while for the model FEM-F is of 146kN, which means a difference of 16,4% in the favour of the model FEM-5.
- in order to compare the bearing capacity evaluated according to the C230/89 design guide (147kN) with the numerical values, the base model (FEM-F) settlement was imposed to 16mm. For this value of settlement corresponds a bearing capacity of 75 kN of the foundation basis (model FEM-3) which is about 51% of the total bearing capacity. The difference of 49% or 72kN is due to friction between the lateral faces and the soil. This share of forces is different from the normative design, according to which the force developed by friction of lateral faces is of 44% of the total bearing capacity;
- for the prismatic shape of a foundation unit as is the model FEM-3, the friction developed by the lateral forces increase the bearing capacity by about 21% as compared to the FEM-3NF model;

4. Environmental Impact Analysis

The potential environmental impact was evaluated relating to indicators such as climate change, ozone depletion, acidification, eutrophication, resource use and water scarcity, using life cycle assessment method (LCA) [9], following the rules of EN 15804 [10] and EN 15978 [11]. The goal of the study was to prove the effectiveness of quick foundation systems by comparing precast wedge foundations with usual prismatic-shape foundations. The dimensions of each foundation type were chosen in addition to comply with the same bearing capacity.

The declared unit of the analysis was one specimen of foundation unit (one precast foundation unit and one prismatic cast-in place foundation unit).

The assessment includes the following life cycle stages: Product stage: A1-A3 (raw materials extraction, transport to the manufacturer, manufacturing), Construction stage: A4-A5 (transport to the construction site, installation/construction), End-of-life stage: C1-C4 (deconstruction/demolition, transport to waste processing, waste processing for reuse, recovery and/or recycling, disposal). In the evaluation, the potential environmental impact was weighted using GaBi Product Sustainability Software [12] along with Ecoinvent 3.6 Life Cycle Inventory database [13].

4.1 System boundaries

The assessment was determined considering the following construction materials:

- precast wedge foundation: 0.156 m³ C20/25 concrete, 56.26 kg steel rebars, 0.081 m³ mortar hand-mixed on-site;
- cast-in place prismatic foundation: 0.324 m³ on an equivalent design of a regular prismatic foundation with the 60x60cm in section and 90cm height. C20/25 concrete.

In the construction stage, the distance considered for the transportation of construction materials / precast wedge foundation from the manufacturer to the building site was 20 km (as the building site is located near a major city) using an Euro 4 truck (diesel driven, 2.7 payload capacity) with 60% utilization rate of the payload capacity by mass and a return journey of the empty trucks taken into account. For the excavated soil it was included in the assessment a 15kW digger, while for the installation of the precast wedge foundation was considered a 3t auto crane.

The transportation of workers to the building site was excluded from boundary conditions of the analysis as well as the manpower. Also, the flows related to the production of transport vehicles heavy equipment, building of production plants, credits associated with temporary (carbon) storage are excluded from current assessment.

The impact of the foundation systems in the Use Stage was not integrated in the analysis and was considered to be null since after the installation completion, the foundations do not require supplementary technical operations and no emissions occur to the environment during use stage.

The End-of-life Stage covered a 100% reuse scenario for the precast wedge foundations and 100% waste scenario for the additional mortar needed for interlocking of precast wedge foundations. For monolithic prismatic foundations (three main aspects headed to the 100% waste scenario: Romania has no recent data on the quantities used for backfilling or for crushed concrete and bricks used for road constructions; there are few facilities in the country for the treatment/recycling/recovery of the construction waste [14] and secondary raw materials are more expensive than natural aggregates [15] which leads to a significant low, close to non-existent, rate of concrete recycling).

For the foundation removal a demolition hammer was included in the assessment - 700W jack hammer for the interlocking mortar added to the precast wedge foundations and 1750W demolition hammer for the monolithic foundations. For the extraction of the precast wedge foundations was considered a 3t crane, while for concrete waste loading in trucks, a 100kW excavator was added to the analysis. The distance considered for the transportation of demolition waste materials from the building site to the construction waste dumping was 30 km using an Euro 4 truck (diesel driven, 2.7 payload capacity) with 70% utilisation rate of the payload capacity by mass and a return journey of the empty trucks taken into account.

In the present study the waste processing was considered to be realized by hand, on site (considering the relatively small quantity of the mortar added to the precast wedge foundations) and therefore, C3 Module (waste processing) is missing from the LCA and considered to have no potential environment impact in the assessment.

The LCA models and boundaries are presented in Fig. 9 for the precast wedge foundation and Fig. 10 for the cast-in place foundation.

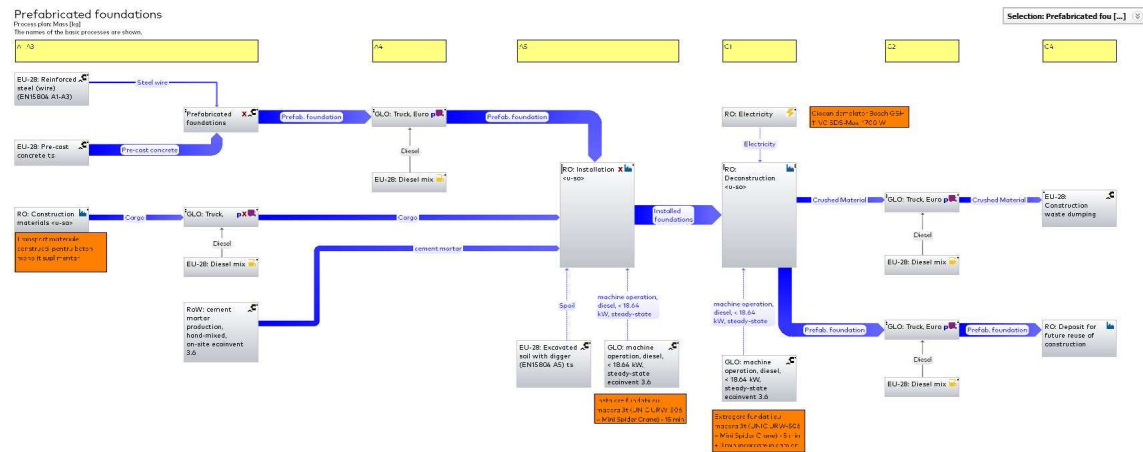


Figure 9. Precast wedge foundations system boundary.

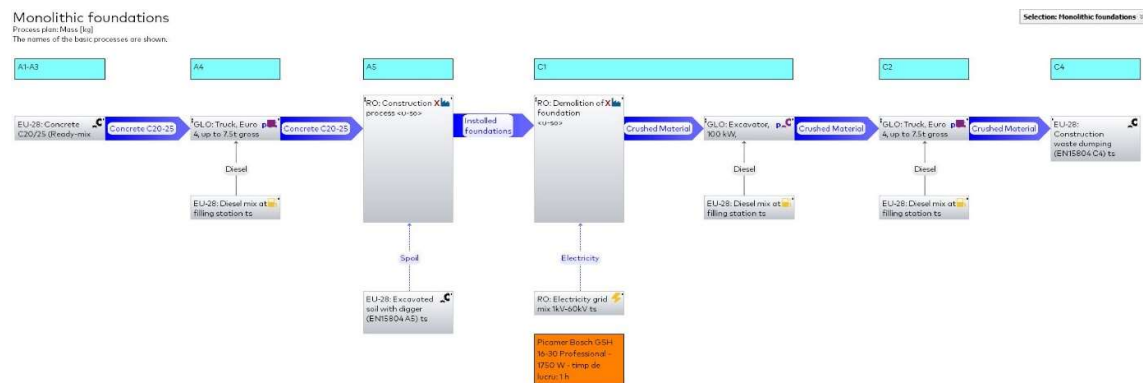


Figure 10. Monolithic foundations system boundary.

4.2 Results of the life cycle assessment

The environmental impact results of the assessment are shown in Table 1 for all 13 impact indicators requested by the newest amendment of EN 15804. Modules A1-A3 are major contributors to total emissions for most of all environmental impact indicators (12 out of 13), representing 42-80% from the total emissions reported.

The next module recording important amount of emissions is Deconstruction/demolition Module, which can register up to 46% of the total emissions. A particular specification has to be underlined when looking to Climate Change (biogenic) results, where negative values were recorded: this is as a result of the fuels burning (regional diesel mix at filling station contains biogenic components blended to the fossil fuel) and the negative values represent the CO₂ (that has already been absorbed during biomass growth) emitted to the biosphere-atmosphere system during biomass combustion. When comparing the two foundation systems, the highest emissions are recorded in modules A1-A3, A5 and C2 for the precast wedge foundations (up to 60% more emissions than monolithic foundations), while monolithic prismatic foundations register a high rate of emissions in modules A4, C1 and C4 (up to 4.5 times higher

emissions that precast wedge foundations). Even though the total amount of emissions in modules A-C appointed precast wedge foundation system as the system with the highest environmental impact, the benefits beyond the system boundary, calculated in module D, reveal a potential in preventing up to 58% of the total emissions by integrating the foundation system in a new life cycle (reusing the precast wedge foundation system). The impact considered, involving potential environmental credits generated by future lifecycles, is based on the impacts of the reuse of construction materials mutually conducted. The calculation is based on the inputs and outputs of recycled and reused materials upon the impact of the virgin material production [16].

Figure 11 presents comparative LCA results for the assessed foundation systems, using Climate Change environmental impact indicator as a pointer. As provided by the CEN/TC 350 methodology, benefits and loads beyond the system boundary (Module D) are not aggregated with the life cycle impacts (Modules A to C). The LCA potential savings in the Climate Change are expressed as negative values, while positive values define burdens of material utilisation.

Table 1. LCA results using environmental impact indicators (upper row: precast wedge foundations' contribution; inferior row: monolithic prismatic foundations' contribution).

Environmental impact indicators	Unit	Modules A1-A3	Module A4	Module A5	Module C1	Module C2	Module C4	Total A-C	Module D (potential benefits)
Climate Change	[kg CO ₂ eq.]	1.15E+2	6.09E+0	1.38E+0	7.71E-1	1.61E+1	2.38E+0	1.42E+2	-7.34E+1
		7.19E+1	9.25E+0	3.61E-1	2.31E+0	1.03E+1	1.09E+1	1.05E+2	0.00
Climate Change (fossil)	[kg CO ₂ eq.]	1.14E+2	6.05E+0	1.38E+0	7.71E-1	1.60E+1	2.58E+0	1.41E+2	-7.30E+1
		7.18E+1	9.19E+0	3.59E-1	2.37E+0	1.02E+1	1.18E+1	1.06E+2	0.00
Climate Change (biogenic)	[kg CO ₂ eq.]	7.73E-1	-1.0E-2	1.07E-4	2.67E-4	-2.7E-2	-2.0E-1	5.32E-1	3.05E-1
		-2.41E-2	-1.6E-2	-2.8E-4	-7.2E-2	-1.7E-2	-9.4E-1	-1.06E+	0.00
Climate Change (land use change)	[kg CO ₂ eq.]	9.27E-2	4.93E-2	2.19E-3	7.50E-5	1.30E-1	7.42E-3	2.82E-1	-5.18E-2
		5.44E-2	7.49E-2	2.87E-3	1.30E-2	8.33E-2	3.40E-2	2.62E-1	0.00
Ozone depletion	[kg CFC-11 eq.]	1.65E-6	1.1E-15	2.40E-7	1.28E-7	2.9E-15	9.6E-15	2.01E-6	-4.7E-13
		1.11E-13	1.7E-15	4.3E-17	1.2E-14	1.9E-15	4.4E-14	1.7E-13	0.00
Acidification terrestrial and freshwater	[Mole of H ⁺ eq.]	2.87E-1	3.55E-2	1.10E-2	4.68E-3	9.37E-2	1.85E-2	4.50E-1	-1.51E-1
		1.70E-1	5.40E-2	4.77E-3	1.10E-2	5.97E-2	8.47E-2	3.84E-1	0.00
Eutrophication freshwater	[kg P eq.]	4.61E-3	1.85E-5	4.07E-5	2.13E-5	4.90E-5	4.43E-6	4.75E-3	-9.39E-5
		3.52E-5	2.82E-5	1.08E-6	5.14E-6	3.13E-5	2.03E-5	1.21E-4	0.00
Eutrophication marine	[kg N eq.]	8.09E-2	1.71E-2	4.72E-3	1.76E-3	4.50E-2	4.76E-3	1.54E-1	-3.85E-2
		6.16E-2	2.59E-2	2.15E-3	4.11E-3	2.87E-2	2.18E-2	1.44E-1	0.00
Eutrophication terrestrial	[Mole of N eq.]	8.92E-1	1.89E-1	5.18E-2	1.93E-2	5.00E-1	5.23E-2	1.70E+0	-4.16E-1
		6.76E-1	2.88E-1	2.36E-2	4.53E-2	3.18E-1	2.39E-1	1.59E+0	0.00
Photochemical ozone formation - human health	[kg NMVOC eq.]	2.44E-1	3.33E-2	1.49E-2	5.46E-3	8.77E-2	1.44E-2	3.99E-1	-1.30E-1
		1.63E-1	5.05E-2	6.98E-3	1.16E-2	5.58E-2	6.60E-2	3.54E-1	0.00
Resource use, mineral and metals	[kg Sb eq.]	2.99E-3	4.92E-7	1.72E-6	9.51E-7	1.30E-6	2.32E-7	2.99E-3	-8.32E-6
		2.15E-6	7.48E-7	2.54E-8	3.04E-7	8.32E-7	1.06E-6	5.12E-6	0.00
Resource use, energy carriers	[MJ]	9.19E+2	8.12E+1	1.87E+1	1.09E+1	2.15E+2	3.38E+1	1.28E+3	-6.62E+2
		3.73E+2	1.23E+2	4.72E+0	3.28E+1	1.37E+2	1.55E+2	8.26E+2	0.00
Water scarcity	[m ³ world equiv.]	1.69E+1	5.94E-2	3.61E-2	4.71E-2	1.57E-1	2.70E-1	1.74E+1	-8.29E+0
		4.99E+0	9.02E-2	3.17E-3	1.35E-1	1.00E-1	1.24E+0	6.56E+0	0.00

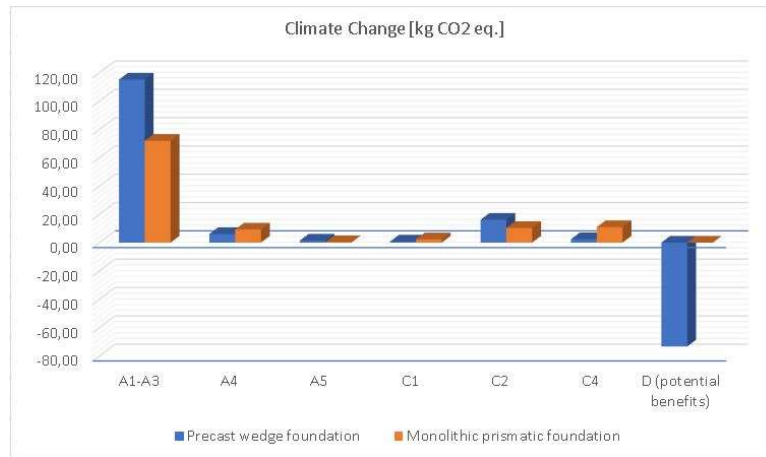


Figure 11. LCA results expressed by the Climate Change indicator

The LCA results for the assessed foundation systems show, as well, for precast wedge foundations higher values of the amount of resources use in the production stage and overall (modules A to C) when compared to cast-in place prismatic foundations. Still, as occurred in case of environmental impact indicators, the potential savings produced by future lifecycles of the precast wedge foundations are between 72% and 92% of the total resource use amounts. Table 2 shows total use of renewable and non-renewable primary energy resources of the two assessed foundation systems for each module of the life cycle assessment. Negative values define potential savings, while positive values represent loads acquired by material utilisation.

Table 2. LCA results expressed by the Climate Change indicator

Resource use indicators	Unit	Modules A1-A3	Module A4	Module A5	Module C1	Module C2	Module C4	Total A-C	Module D (potential benefits)
Total use of renewable primary energy resources (PERT)	[MJ]	170,40	4,70	0,28	1,27	12,42	4,43	193,50	-156,90
		43,50	7,14	0,27	6,28	7,94	20,28	85,41	0,00
Total use of non-renewable primary energy resources (PENRT)	[MJ]	919,84	81,55	18,67	10,94	215,66	33,85	1280,50	-663,43
		373,44	123,92	4,73	32,93	137,80	154,91	827,73	0,00

5. Conclusions

The paper presents a study made on single-unit foundations, loaded under axial compression forces. The study is based on two experimental tests made on wedge foundation specimens inserted in dug holes. The interlocking with the surrounding foundation soil was made with cement mortar. The resistance checking, including the FE modelling is completed by an environmental analysis.

The experimental tests demonstrated that the wedge foundations can overtake important axial loads, and a part of these loads are transmitted through lateral faces, by friction. On the other hand, the variability of the geotechnical parameters of the foundation soils as well as the way of assuring the contact, will lead to important variability of the obtained results.

The FE numerical analyses prove that tapered faces of the foundation overtake important shares of the total bearing capacity of the foundation (49%) similar to the values resulted from the normative design (44%). Also, the FE numerical study proves that an equivalent foundation unit of prismatic shape with the median cross-section of the wedge foundations, lead to a higher bearing capacity in comparison to the wedge foundations. This is due to the increase of bearing capacity due to lateral face friction with the surrounding foundation soil.

The assessment of the environmental impact considered two different study-cases, where the foundation systems are either usual prismatic foundations or re-usable precast wedge foundations. The assessment emphasized the feasibility of wedge foundations and the environmental benefits of construction elements based on the reuse concept strategy.

The Life Cycle Assessment results showed that a reuse concept strategy in foundation systems is an approach that generates environmental benefits while saving more than 42% of the GHG emissions and more than 31% of the resource use, in the production stage (A1-3).

The end-of-life model of construction products play an important role in the environmental impact, as buildings require a significant amount of material resources and demand high energy consumption.

Acknowledgments

This work was supported by a grant of the Romanian Ministry of Research and Innovation, CCCDI – UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0391 / CIA_CLIM – Smart buildings adaptable to the climate change effects, within PNCDI III.

References

- [1] MDRAP, Design and execution guide of punched holes for foundations, index C 230-89 (in Romanian).
- [2] M. Păunescu, M. Marin, Modern Solutions for Direct Foundations, Facla, Timișoara, 1986 (in Romanian).
- [3] S Jin-Cheng, Axial Compressive Capacity of Short Tapered Piles in Sand, U.P.B. Sci. Bull., Series D, Vol. 81, Iss. 2, 2019 ISSN 1454-2358.
- [4] A. A. Bartolomei and A. B. Ponomarev, Experimental Investigations and Prediction of Settlements of Conical-Pile Foundations, Soil Mechanics and Foundation Engineering, Vol. 38, No. 2, 2001
- [5] J. Q. Wei, Experimental Investigation of Tapered Piles, thesis, Faculty of Graduate Studies, The University of Western Ontario, August, 1998
- [6] MDRAP, Standard on design of shallow foundations, index NP112-2013 (in Romanian)
- [7] MDRAP, Standard on site testing of sample piles and foundation piles, index NP045-2000 (in Romanian)
- [8] Midas GTS NX 2019 v1.1, User Manual, MIDAS Information Technology Co., Ltd.
- [9] CEN/SS S26. EN ISO 14044:2006+A1:2018. Environmental management - Life cycle assessment - Requirements and guidelines - Amendment 1 (ISO 14044:2006/Amd 1:2017)
- [10] CEN/TC 350. EN 15804:2012+A2:2019. Sustainability of Construction works - Environmental product declarations - Core rules for the product category of construction products - Amendment 2 (EN 15804:2012/Amd 2:2019)
- [11] CEN/TC 350. EN 15978:2011. Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method
- [12] Sphera Solutions, GaBi: Product Sustainability Software. Version 9.2.1 (2020).
- [13] Ecoinvent Life Cycle Inventory LCI database. Version 3.6 (2019)
- [14] EC. Construction and Demolition Waste Management in Romania (2015). Available online: http://ec.europa.eu/environment/waste/studies/deliverables/CDW_Romania_Factsheet_Final.pdf (in Romanian)
- [15] F.-C. Mihai, Construction and Demolition Waste in Romania: The Route from Illegal Dumping to Building Materials, Sustainability, 11: 3179 (2019).
- [16] V. Ungureanu, R. Buzatu, D. Muntean, P. Hradil, S. Vares, Case studies for the implementation of reclaimed elements, Deliverable D7.2 of PROGRESS project, Timisoara, Romania (2019).