GEOTECHNICAL EVALUATION OF SELF-BUILT HOUSING SETTLEMENTS NEAR THE SHORES

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The lake soils that were occupied by constructions cause serious geotechnical problems, but even more so they are linked to the self-construction, self-planning, and self-management of housing and its influence on poorly designed and poorly located support elements on the shores of the lake, in the city, from Puno, Peru. The objective was to determine which factors cause damage to the structures of a self-built house. Technical inspections were carried out on randomly selected homes with moderate and severe construction deficiencies, as well as characterization and dynamic light penetration tests in compliance with the technical standard E.050 and E.060 of the National Building Regulations of Peru. The results reveal that 60% of the interviewees were unaware of the studies and designs that should be carried out; In addition, it indicates that the houses present negative symptoms such as fissures and cracks in different parts of the houses analyzed, linked to settlement, humidity, and salinity, with consequences in the weakening of the foundations of the houses. It is concluded that there was negligence by the owners in the design and construction of the foundations of their houses, without technical direction and professional supervision with uncontrolled fillings and unreliable construction procedures, it is advisable to go to specialists to avoid future problems in interaction soil-structure.

Keywords: Self-built house, Informal urban settlements, Lacustrine soil, Construction.

1 INTRODUCTION

Housing is a universal human right, while urbanization is an increasing trend worldwide and even more so in Latin America; however, there is a shortage of housing (Gonçalves and Gama 2020). Many people decide to self-build, in areas that do not have adequate conditions, a situation that leads to disastrous results (Ibem et al. 2012, Marais and Ntema 2013). Inadequate land management and informal urban allotments with poor land conditions for urbanization have caused damage to self-built housing (Lyu et al. 2018, Boateng 2020). Damage due to foundation and structural failures has a close relationship with differential ground settlement (Carretero-Ayuso and Pinheiro-Alves 2021), which requires compliance with public standards (Agapiou and Yakubu 2019) and increased soil mechanics testing (Eze et al. 2023).

The city of Puno is limited by the surrounding mountains and Lake Titicaca to the west, which restricts urban expansion for housing construction due to its rugged topography and the presence of the lake. Therefore, residents see the option of building in the remaining spaces and land with imminent dangers, with geotechnical risk, flooding, and unstable soils. Such is the case of the Santiago de Chejoña neighborhood, located on the shores of Lake Titicaca, where housing is currently being built more intensively on land previously occupied by the lake. The alarming
situation is the uncontrolled earthworks or landfills in the area, with soils of dubious origin from materials and construction waste, organic soils, rocks, and heterogeneous soils in its structure in order to raise the ground level, to start the construction of a building. Thus, the use of unclassified fill materials creates difficulties because when they are mixed with natural soil it is very difficult to determine their real characteristics, further aggravating this condition.

The objective of this research was to determine which factors cause damage to the structures of a foundation of a self-built house.

2 MATERIALS AND METHODS

2.1 Study Area

This research was carried out in the Santiago de Chejoña neighborhood of the city of Puno, Peru, specifically in the area where landfills are made on the shores of Lake Titicaca to build houses, at coordinates 15°51'24.5"S, 70°00'15.3"W, altitude 3827.00 m asl, located southeast of the city (Figure 1).

![Figure 1. a) Location of study area. b) House with foundation failures. c) Wall with a crack.](image)

2.2 Methods

2.2.1 Surveys

For the selection of the dwellings, previous research was carried out. We worked with statistical tools to choose the most representative ones, the most exhausting part of the work consisted of the survey to the owners, because the great majority was opposed to the questions and the inspection of their houses since there was certain distrust of the owners and to the technical surveys carried out.

The research technique was observation and surveys, carried out to each owner of the self-built houses, to evaluate geotechnical, structural, and constructive aspects of the foundations of their houses. The sample size "M" was obtained through Eq. (1), according to the statistical
formulations, technical surveys were carried out in the randomly chosen homes that present moderate and serious construction deficiencies and verified compliance with the standard E.050, E.060 of the Peruvian National Building Regulations (MVCS 2021). The sample was stratified according to the number of floors in high (Table 1).

\[ M = \frac{z^2 \times (p \times q) \times N}{e^2 \times (N-1) + z^2 \times (p \times q)} \]  

(1)

where:  
M = Sample size;  
z = 1.96 (95% confidence level) normal distribution;  
e = Sampling error 5%;  
p = Proportion of dwellings of interest for the research;  
q = Proportion of dwellings of no interest for the evaluation;  
N = Total number of private dwellings to be evaluated.

The technical surveys included questions related to the evaluation of the design of the house, the technical direction in construction, dimensioning of footings or support elements, soil mechanics analysis, strength analysis of the concrete used for these footings, presence of structural damage such as cracks and fissures, humidity and salinity (Table 2). The survey responses were collected, systematized, and processed using an Excel spreadsheet (2021: USA). Through this inquiry procedure and direct observation in situ, it was possible to know how the surface foundations were built and their current condition.

### 2.2.2 Geotechnical evaluation

In addition to the surveys aimed at houses with moderate and severe construction deficiencies, the evaluation also includes soil characterization tests, granulometry, consistency limits, and light dynamic penetration (LDP), according to ASTM standards and Peruvian technical standards (NTP), in compliance with the requirements of the Peruvian National Building Regulations (MVCS 2021) and its standard E.050. The samples were extracted from the study area and distributed in four open pit excavations as shown in Figure 1.

### 3 RESULTS

#### 3.1 Surveys

In the initial inspection of the buildings, it was found that the residents of the Santiago de Chejoña neighborhood in the city of Puno build their homes to make them durable over time, mistakenly thinking that building them with steel and concrete will make them more durable, safe and functional. However, self-built houses have a short service life, but they present serious structural and construction problems in terms of their supporting elements, that is, they present defects in the foundations and structures (columns, beams, walls).

<table>
<thead>
<tr>
<th>Stratum</th>
<th>No. of floors</th>
<th>Total housing</th>
<th>Sample (M_h)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2</td>
<td>52</td>
<td>23</td>
<td>70%</td>
</tr>
<tr>
<td>II</td>
<td>3</td>
<td>18</td>
<td>8</td>
<td>24%</td>
</tr>
<tr>
<td>III</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>6%</td>
</tr>
<tr>
<td>Total</td>
<td>74</td>
<td>33</td>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

The study area has a total of 327 houses distributed in three strata: 177 are empty and/or fenced lots, 76 are one-story houses, 52 are two-story houses, 18 are three-story houses and 4 are four-story houses; of these, 23 houses (70%) from stratum I, 8 houses (24%) from stratum II and 2 houses (6%) from stratum III were taken as corrected \(M_h\) samples, making a total corrected sample
of 33 analyzed houses. The highest percentage of houses is in stratum I and the lowest percentage of houses are in stratum III (Table 1).

Table 2. Variables analyzed in the study of constructed housing.

<table>
<thead>
<tr>
<th>Variable Notation</th>
<th>Description</th>
<th>Yes</th>
<th>No</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>y1</td>
<td>You have your plans for your home</td>
<td>62%</td>
<td>38%</td>
<td></td>
</tr>
<tr>
<td>y2</td>
<td>Land clearing for self-built homes</td>
<td>45%</td>
<td>55%</td>
<td>Most of the cleanup was minimal and in targeted areas.</td>
</tr>
<tr>
<td>y3</td>
<td>Layout and stakeout for foundations</td>
<td>0%</td>
<td>100%</td>
<td>Self-built houses are referenced with tape measures.</td>
</tr>
<tr>
<td>y4</td>
<td>Preparation of the bottom of the foundation</td>
<td>5%</td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td>y5</td>
<td>Stripping of over foundation at the top for bricklaying</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>y6</td>
<td>Ground improvement for the foundation</td>
<td>10%</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>y7</td>
<td>The footing is provided with a moisture protection screed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>y8</td>
<td>Presence of moisture and salinity in foundations and walls</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>y9</td>
<td>Symptomatology of housing settlements</td>
<td>97%</td>
<td>3%</td>
<td>Settlement manifests in fissures and cracks</td>
</tr>
</tbody>
</table>

According to the variables analyzed in the houses built in the three strata, 62% of them have their construction plans, 55% had only minimal cleaning and in focused parts, 95% had no preparation of the foundation base, 85% during the construction process had scratching of the over foundation at the top for bricklaying, 90% had no improvement of the soil for the foundation, 52% have a floor covering to protect against humidity and 85% have humidity and salinity in the over foundations and walls (Table 2).

3.2 Geotechnical Evaluation

Soil sample C-01 has an allowable load of \( q_a = 21.57 \) kPa (0.22 kg/cm²), with a predominance of inorganic silt of high plasticity (MH), with a fully saturated soil, with a moisture content of 108.54% and a liquid limit LL=104.49%, plastic limit PL=66.31%, plasticity index PI=38.18%, most of them are square type foundations. Soil sample C-02 has an allowable load of \( q_a = 14.71 \) kPa, with a predominance of inorganic silt of high plasticity (MH), a fully saturated soil, with a moisture content of 139.06%, and LL=102.27%, PL=61.95%, PI=40.32%, with a predominance of square footings and reinforced foundations. Soil sample C-03 has an allowable load of \( q_a = 44.12 \) kPa, with a predominance of inorganic clay of high plasticity (CH), with a fully saturated soil, with a moisture content of 123.70%, and LL=92.75%, PL=39.45%, PI=53.30%, with a predominance of rectangular footings. Soil sample C-04 has an allowable load of \( q_a = 29.42 \) kPa, with a predominance of inorganic silt of high plasticity (MH), with a fully saturated soil, with a moisture content of 116.50% and LL=130.35%, PL=101.81%, PI=28.54%.

Figure 1b shows the typical characteristics of a house in the study area, in which fissures that evolved into cracks were manifested, with exaggerated settlements in the fill areas on the shores of the lake. Vertical cracks indicate that they are the product of vertical settlement and diagonal cracks are caused by diagonal tension (Figure 1c).

Of the houses built in the three strata of the study area, 38% of the houses have cracks or cracks in the main beams, 30% of the buildings have fissures or cracks in the load-bearing walls, 22%...
have fissures or cracks in the columns, 10% of the buildings have cracks in the foundations (Table 3).

Table 3. Symptomatology of settlements in structural elements.

<table>
<thead>
<tr>
<th>Description</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fissures or cracks in columns</td>
<td>22%</td>
</tr>
<tr>
<td>Fissures or cracks in load-bearing masonry</td>
<td>30%</td>
</tr>
<tr>
<td>Fissures or cracks in main beams</td>
<td>38%</td>
</tr>
<tr>
<td>Cracks in over foundations</td>
<td>10%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
</tr>
</tbody>
</table>

4 DISCUSSION

The soils studied are deformed due to their inadequate mechanical properties to support loads, when mixed with natural soil they are heterogeneous soils without any engineering control during the filling of land, it is not an elastic material and the response to load solicitations is inelastic, and of difficult prediction, being the nature and distribution of the soils, determinants of the pathological casuistry.

The highest percentage of self-built houses present deficiencies in their structural elements, such as cracks in the load-bearing masonry walls and main beams, because these houses are built in inadequate areas (Gonçalves and Gama 2020), because the decisions taken are not the right ones, with often disastrous results (Ibem et al. 2012, Marais and Ntema 2013).

Land management and urban habitation are very important to achieve the urbanization and construction of housing on land suitable for this purpose and thus avoid future damage, and contribute to the objectives of structural design, providing safe, economical, and functional housing (Lyu et al. 2018, Boateng 2020).

Consequently, sooner rather than later, self-built houses, due to the weight they represent, could begin to have construction problems, from almost imperceptible fissures, cracks, settlements, and subsidence, to collapses (Li and Li 2019), due to the overload to which they are subjected by the structure. Due to the low bearing capacity values, the foundations and structures redistribute the stresses to the other structural elements, and the possibility of expansive soils, which is frequent in clayey areas, must also be taken into account (Gómez et al. 2019, Pilares-Hualpa et al. 2021).

5 CONCLUSION

The results of the surveys of the stratified samples showed that 97% of the houses showed symptoms of differential settlement such as cracks and fissures and general failure of the structural system.

The natural soil types in the study area have a predominance of high plasticity inorganic silt (MH) and high plasticity inorganic clay (CH), partially to fully saturated from 3 meters depth. These soils trigger differential settlement failures in the houses located on the shores of the lake and in frequent cases fissure as the first symptom, evolving to cracking as the second symptom and the separation of confining elements as the final consequence due to inadequate fill material and compaction.

The owners resort to self-construction of a house without the technical participation of the professional in geotechnical and structural aspects, because it is very little value, due to the lack of knowledge that it represents in the adequate construction of houses. Therefore, it is recommended to carry out field and laboratory tests, as well as technical supervision during the construction
The process of the houses, in addition, specialists and academics continue with research on the subject that contributes to the achievement of the objectives of the structural design.

Acknowledgments

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References


