General design considerations for applying thermal insulation layers underneath foundations of buildings placed within the main seismic regions of Romania

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Abstract. Worldwide common efforts towards developing a sustainable, competitive, eco-friendly and efficient built environment have led to a new legal and technical spectrum of rules and requirements for high energy performance buildings. Provision of solutions for a continuous thermal envelope is sometimes essential in designing such buildings. Mitigating, as much as possible, the thermal bridging phenomenon is highly important and should be accounted from the very beginning in the design process. This issue can be addressed through various solutions when it comes to thermally insulating the superstructure but can be quite challenging and limited at infrastructure level, particularly for buildings set in areas exposed to earthquakes. This paper explores existing technical literature, local codes, norms and standards, with the twofold purpose of: (1) providing a view on the relevant available research and design prescriptions; and (2) outlining incipient general design considerations related to the feasibility of applying specific thermal insulation materials beneath buildings located within the main seismic regions of Romania.

1. Introduction
Global issues and concerns related to climate change, greenhouse gas (GHG) emissions, and energy safety and independency led to changes in the legal framework related to the building industry. New building concepts have arisen, such as nearly zero-energy, zero-energy, or even plus-energy buildings, and provisions and requirements for developing an energy efficient built environment are already enforced in different parts of the world. For example, relatively new requirements are set by the EU Directive 2010/31/EU on the energy performance of buildings (EPBD) and Directive 2012/27/EU on energy efficiency. Among other, the EU Directive 2010/31/EU defines requirements for a new concept of buildings, generally acknowledged as “nearly zero-energy buildings” (nZEB).

As defined within the EPBD, nZEB stands for “a building that has a very high energy performance”, which refers to a “nearly zero or very low amount of energy required”. This legislation has been transposed by the EU member states into standards and norms, with a view to provide indicators of performance and threshold limit values that would define and allow classification of buildings as nZEB. Requirements vary from one region to another, but implementation of specific design principles is essential for having high energy efficient buildings as final product. However, if some detail design solutions work in one area (e.g. in seismically inactive areas), sometimes they may not be suitable elsewhere (e.g. in areas exposed to earthquakes). In some cases, this may refer to applying thermal
insulation materials in structurally sensible sections of the building. Having this in mind, it is expected that the design process would extensively consider ways to maximize the energy efficiency of buildings while not endangering their structural integrity. Given the emerge of new materials together with new technical perspectives, as well as the new and more demanding specific requirements from clients or new norms, designers may sometimes be placed in “grey areas” characterized by a high level of uncertainty whether a certain design solution is suitable or not. This sort of issues can be easily settled if designers have access to clear standards / norms / codes and extensive studies to account for the effective challenges that may be encountered in the design process. An important example refers to the recommendation for high energy-efficient buildings to have a fully continuous thermal envelope (enclosing parts of the building for which internal climate should be controlled and as much as possible independent from the outside environment). Theoretically, in certain cases, this may imply the need for inserting thermal insulation underneath foundations, which may come as normal practice in seismically inactive areas but be problematic in areas exposed to earthquakes.

In Romania, the current technical provisions are very limited regarding the possibilities of applying thermal insulation materials at the infrastructure level of buildings, apart from imposed limits and requirements related to absolute/relative settlements. The technical provisions do not directly address the subject of multi-layered embedment of buildings or of the soil-structure-interaction through direct and exhaustive design prescriptions and guidelines. However, even if somehow “segregated” (i.e. usually the superstructure is treated separately from the infrastructure), general prescriptions for structural behaviour, both for the superstructure and infrastructure are made. With certain limitations, these prescriptions can be used to establish certain requirements for material properties and their mechanical characteristics. Such requirements can also be determined in what concerns the thermal insulation materials that might be used at infrastructure level.

2. Thermal insulation beneath the foundation – advantages, available materials and technologies, examples

Studies show that ground heat transfer plays an important role in the overall thermal performance of buildings [1].

Generally accepted advantages of having a continuous thermal envelope and, implicitly, of thermally insulating the foundation (whether slab or strip) are directly related to the avoidance of thermal bridging, elimination of draught effect / cold surface radiation phenomena, reduction of energy demand and costs. These are important aspects that help provide better living conditions in healthier indoor environments, characterised by a higher level of independency from the outdoor climatic conditions and inherently a higher level of control for the indoor climate and living parameters. In addition, the elimination of thermal bridging, could help avoid in the long term some potential negative impacts on the elements of buildings and would favour less frequent maintenance works or avoid even more serious damages if structural elements are harmed (e.g. water vapour condensation and ingress in areas subject to thermal bridging). For this, sometimes advanced heat transfer / hygrothermal modelling is recommended for properly identifying best solutions to mitigate such risks.
The image is showing a continuous Thermal Insulation (TI) layer on the entire cross-section of a building (hatched) – the only “interruptions” are on the right-hand side, where windows are positioned (which are part of the building envelope as well). Also, in this example, the TI layer continues underneath the building. Such solution may be explored when trying to find ways to mitigate thermal bridging and assure increased energy efficiency, especially when the underground level(s) are subject to heating or cooling.

2.1. Materials available on the market
For reasons related to cost and without taking into account advanced materials options and perspectives (e.g. aerogel sheets, nano insulation materials, high-strength thermal breaks for structural connections), the most common materials that are usually considered suitable for thermally insulating the foundations of buildings, while being applied beneath concrete slabs, are polystyrene (extruded: XPS – which is expected to show really good mechanical characteristics, be less sensible to water, but rather have a more accelerated degrading of its thermal resistance properties over time and a higher manufacturing carbon footprint when compared to EPS; or expanded: EPS – usually expected to have lower mechanical characteristics, be more sensible to water, but have higher stability of its thermal resistance properties over time & smaller manufacturing carbon footprint compared to XPS) and foam glass aggregates/gravel [2][3].

| Material                      | Maximum Compressive Strength [kN/m²] | Thermal Conductivity [W/mK] | Deformation [%] |
|-------------------------------|-------------------------------------|----------------------------|-----------------|
| Jackodur KF 700 XPS           | 700                                 | 0.027                      | < 10            |
| Sundolitt EPS S500            | 500                                 | 0.038                      | < 10            |
| Foam glass gravel (Geocell)   | 570                                 | 0.08 (dry material)        | < 10            |

With a higher compressive strength, resistance to water ingestion, reduced long-term creep and relatively good durability, it can be concluded that XPS boards can be a suitable candidate for thermally insulating foundations placed in seismic prone areas. However, other types of materials may be explored and might be a better choice, based on the desired criteria, available information, and project specifics.

2.2. Standard solutions, usually for non-seismic areas / regions with low risk for seismic hazard
Various design solutions are available and generally used in concepts that relate to high energy performant buildings. For such concepts, a key endeavour is the “complete” elimination of the thermal bridging phenomenon. Two examples of design solutions that can be used to mitigate the thermal bridging at foundation level are presented in Figures 2 and 3.
Figure 2. Proposed cross-section for applying extruded polystyrene JACKODUR XPS under the foundation, as suggested by producer (1 – levelling layer; 2 – e.g. JACKODUR KF 300/500/700 Standard; 3 – Polyethylene film; 4 – Foundation slab; 5 – Cement-based waterproofing; 6 – Structural waterproofing; 7 – JACKODUR Gefiniret; 8 – Plaster.

Figure 3. Thermal insulation of house foundation slab, using EPS solutions provided by Legalett [4].

Application of thermal insulation materials at foundation level is not “beneficial” only for small housing projects, but can be an option for industrial buildings, halls, or even on multi-level buildings, depending on energy-efficiency requirements and under precise considerations for structural safety.

An example of thermal insulation materials being applied underneath a building foundation is the Energy-Saving Construction Laboratory of the Cracow University of Technology, a five-story office building (nZEB) in Cracow. In this project, two layers (50 mm and 100 mm) of XPS polystyrene have been inserted beneath the foundation slab of the building. The usage of polystyrene beneath the foundation slab was subject to a specific study performed by polish authors Rafał Szydłowski and Wojciech Kalisz, which revealed excellent behaviour of the material. One conclusion of their study was that “the change in the thickness of the 150 mm layer of XPS under the foundation slab of the five-story reinforced concrete building exceeded slightly 1 mm.” Also, the study indicated that this “value was reached at the stresses equal to 115 kPa (value from numerical calculations).” Such a small change in insulation thickness being considered not significant for the total settlement of the building. [5]

However, the above referenced study and general considerations made when assessing the behaviour of the TI layer and its influence on the superstructure and on the superstructure seismic response; (2) the mechanical characteristics of the layer and its capacity to withstand the seismic loads that are incoming from the superstructure (limited deformation) - in order for it to be able to further transfer these loads to the subsequent ground layers, while preserving an “elastic” / quasi-elastic behaviour; (3) the fact that eventual permanent deformations do not endanger structural safety (4) the behaviour in time of the thermal insulation material; (5) changes in mechanical structure and in the behaviour of the material due to accidental water ingression or due to other potential aggressions of the existing environment (e.g. frost, vibrations, pests, etc.).
3.1. Romanian Standards, Norms and Design Codes
The relevant design codes, standards and/or norms make no reference to the possibility of applying a layer of thermal insulation under the foundation of buildings; on the other hand, there is also no explicit restriction on this matter.

The local earthquake design code P100-2013 requires that the seismic loads are transferred as directly as possible, without any interruptions, from the superstructure to the ground, provided that the foundation and ground will be able to take these loads with no considerable permanent deformations, while taking into account the interaction between the foundation and the ground. [5] Additionally, technical provisions are available for designing surface foundations (i.e. NP 112 – 2014) and geotechnical design (i.e. SR EN 1997-1 and GP 129-2014). Technical guidelines for designing the foundation ground to seismic actions for direct foundations are also provided (i.e. GP014 – 1997), with the scope of delivering an insight on limit state bearing capacity calculations. These technical prescriptions are useful in understanding the main mechanical characteristics and requirements for the ground on which foundations/buildings are set. To better understand the seismic region of Romania, among other, the P100 design code provides maps for (1) design peak ground acceleration values for an average recurrence interval of 225 years and 20% probability to be exceeded in 50 years. (2) zoning based on control periods, Tc, of earthquake response spectrum.

![Figure 4. Peak accelerations in Romania (P100-2013 Code).](image)

![Figure 5. Control Periods of Response Spectrum for Romania (P100-2013 Code).](image)
3.2. Design considerations for the thermal insulation layer underneath foundations

Usually, one important concern when designing the infrastructure of a building is related to the ground beneath building foundations’ bearing capacity and deformation as subject to (seismic) loads; this can be a starting point in discussions related to setting further general acceptance conditions for any thermal insulation layer (or any other type of material) that is to be used underneath buildings or other structures’ foundations.

Annex D of NP 112 – 2014 norm provides conventional pressure values for different types of soil. Apart from high strength rocks, it can be noted that most soil types have conventional pressures (i.e. design pressures) with values similar to the compressive strengths of some sorts of polystyrene (i.e. XPS, EPS or granular). The same norm provides limitations for relative and/or absolute settlement, as shown in Table 2. In lack of specific regulation, it can be understood that, among other, through design, the insertion of a thermal insulation layer beneath the foundation should satisfy these requirements. Some examples of threshold limit values (set by NP 112 norm) for relative and absolute ground settlements corresponding to different types of structures are provided in Table 2.

| Table 2. Example of displacement / settlement threshold limit values provided by NP 112. |
| Construction / Structure Type | Displacement / Deformation [-] | Limit value | Settlement [mm] | Limit value |
|--------------------------------|-----------------------------|-------------|-----------------|-------------|
| Civil (Buildings) and Industrial Frame Structures |                          |             |                 |             |
| a) Reinforced Concrete (RC) without brickwork or panels filling | 0.002 | 80 |
| b) Metallic frames without brickwork or panels filling | 0.004 | 120 |
| c) RC frames with brickwork fillings | Relative settlement | 0.001 | Maximum absolute settlement, $s_{max}$ | 80 |
| d) Metallic frames with brickwork or panels filling | 0.002 | 120 |
| Structures with no additional efforts due to ununiform settlements | 0.006 | 150 |

With enough details on the characteristics of the material, the thermal insulation layer’s influence can be accounted in three-dimensional finite elements modelling software, for better understanding of its impact on structural behaviour, deformations due to seismic loads, etc. Based on the capabilities of the software, this can be done by inserting the layer directly in the model (if the ground can be modelled directly, e.g. software such as QUAKE/W FEM), or by considering its influence on the effective stiffness / reaction of the ground, while modelling the ground-structure interaction through links or springs (e.g. ETABS). This is detailed further under subchapter 3.3.

3.2.1. Overview on the mechanical characteristics of the thermal insulation layer. Manufacturers usually provide technical details within materials data sheets. These may refer to endurance classes, compressive stress and deformations, elasticity modulus, dynamic stiffness, etc. However, sometimes additional studies and tests may be deemed necessary in order to increase the level of certainty and for a better understanding of material behaviour and mechanical characteristics (e.g. shear characteristics, friction with ground / concrete, etc.).

To better understand on how tests on thermal insulation material can be made and what is the expected behaviour of such materials to different types of loading, several studies have been explored.
The previously mentioned study related to the five-storey building in Cracow, Poland, provides information on tests done on XPS polystyrene (i.e. Synthos XPS 70, corresponding to a 700 kPa under the imposed strain of 10%).

(1a) The authors of the referenced study [5] conducted the laboratory tests by using “2 samples of the dimensions of 0.5 × 0.5 × 0.15 m. In order to limit the horizontal deformation of samples, they were placed in a special steel ring. The clearance between XPS and the ring, of the thickness of 7–8 mm, was filled with cement mortar. The first sample was used to test the \(\sigma-\varepsilon\) (strain–deformation) dependence. The load was applied with continuous increase in the XPS thickness loss of 0.5 mm per minute, until gaining the highest load capacity of the material.” [5]

(1b) Additionally, during the construction of the five-story building actual on-site deformation of the XPS layer was monitored in three points, determining a total 1.19 mm deformation, for a 150mm thick layer, under an estimated compression of 115 kPa. This is a good way of better understanding the actual on-site behaviour of the XPS material. Monitoring its behaviour in actual site conditions can be seen as good practice, both for effective works execution quality assurance and also for scientific purposes.

(2) Another study [6] chose different testing procedures (e.g. no usage of perimetral restrain), seeking to determine mechanical characteristics (including the modulus of elasticity - E and shear modulus – G) in order to verify the information provided by the manufacturer and to retrieve sufficient credible data for performing three-dimensional finite element modelling of buildings with a layer of XPS products under the foundation. Such an approach was conducted by the team which elaborated the study “Seismic Aspects of the Application of Thermal Insulation Boards Beneath the Foundations of Buildings” [6]. For this, the XPS products were subject to monotonic and cyclic, compressive and shear loads.

It can be observed from both studies [5][6] that the mechanical properties of XPS were comparable from one test to the other on similar materials, even if testing arrangements were slightly different. Also, it can be seen that there was consistency between the mechanical characteristics of XPS materials produced by different manufacturers and the available data sheets. Overall, the conclusions of the studies are leading to the idea that the XPS has relatively good compressive strength with limited deformation and could be a suitable candidate for being placed underneath the foundations of buildings, even in seismic areas, under certain conditions. Also, it could be considered that the application of such a layer, if certain criteria is met and specific design considerations made, would not negatively and uncontrollably affect the seismic behaviour of structures. Further studies and research are recommended for a better understanding of the available types of materials that could be used as thermal insulation at foundation level, of their mechanical properties and general behaviour, especially for combined dynamic / seismic like loading, but also to what concerns behaviour of such materials over time. This should be done both for a better understanding of the current available materials on the market, but also to find out what improvements should be made and what should be required from new materials.

3.2.2. Considerations for the overall settlement. The local norms (i.e. NP 112 – 2014) prescribe requirements and threshold limit values for two types of settlement: (1) relative settlement, which refers to the difference between the absolute settlements of two nearby foundations, divided by the distance between each other; (2) the absolute settlement, for which both the immediate settlement and long-term settlement should be considered. This should be accounted for any layer under building foundations as well and the estimated deformation (immediate and long-term) of the polystyrene layer should be included in the overall and absolute settlement of foundations under maximum predicted loading. Determining the overall settlement of the building is also a key step in assessing the subgrade reaction, a parameter used in indirect methods for soil-structure-interaction (SSI) analysis.

3.2.3. Considerations for infrastructure rigidity. For buildings with underground levels, extensive considerations should also be made in relation to the requirements for infrastructure rigidity, since the continuous application of thermal insulation of relevant thickness on the outer side of the underground
walls and beneath the foundation may allow for additional displacements at infrastructure level, due to the creation of a more flexible embedding environment (e.g. vertical / horizontal interface). The implications of applying such a layer should be carefully assessed through SSI analysis based on structure specifics and extensive understanding of local ground conditions.

3.3. Modelling the thermal insulation layer underneath foundations and expected influence on structural behaviour

As mentioned before, this can be done directly through dedicated software that can perform a “complete” modelling of both the structure and the local ground conditions, including the thermal insulation (TI) layer. Creating such a model can be difficult and implies advanced studies and geotechnical understanding of the local site conditions. In such case, it may be proven necessary to understand how to properly model the effective ground layers and the interfaces (conditions) between the different layers of materials, and experimental data might be required for this. Such an approach is beyond the scope of this paper, which only aims at offering a general perspective on the design process and considerations, including some introspects on the influence a TI layer with a certain thickness applied at infrastructure level might have on buildings structural behaviour in some hypothetical situations.

An indirect SSI method approach is attempted in order to get a preliminary understanding of the implications of XPS usage at the infrastructure level of a hypothetical building as further described. The SSI is considered and introduced into the models by means of calculation springs with different stiffness values. Several models have been prepared and used in order to compare the general structural behaviour (mainly period and drifts) in different scenarios – i.e. with or without XPS, in two different “site conditions”. More specifically, a hypothetical underground, ground floor and five-storey reinforced concrete / frame structure within the main seismic area of Vrancea (ag=0.4m/s²; Tc=1.6s) was analysed. Two different site conditions were presumed and for each of them several models have been created, to account for normal conditions (i.e. without the TI layer) and for the TI layer influence, while also taking into account modification factors “α”, between the ground reaction to static loading and dynamic “earthquake like” loading, of 2.5 and 5 [7][8]. This is done only for comparison between the different models, as described, and not for structural validation.

The first series of models considered the building placed on a non-cohesive soil with a linear deformation modulus of 27000 kPa, while the second series of models considered the same structure embedded in a cohesive soil with a linear deformation modulus of 18000 kPa. In each case, the overall settlement due to the highest expected loading was determined in accordance with NP-112 national norm. Also, transversal “subgrade stiffness” was considered in the models [9]. The horizontal ground reaction on the outside face of the underground walls was introduced as springs (these values are depth depended) and for this, some hypothetical values have been obtained having as start point the local norm “NP123” [11] for piles design. The reaction/stiffness values were multiplied with the “α” correction factors mentioned earlier and used to model the springs around the outer face of the underground level of the building. The ETABS program was used for modelling the structure and the following considerations should be noted: (1) all models consisted of columns with a section of 0.8x0.8m, beams with a section of 0.3x0.6m, 0.3m thick walls at the underground level, a 0.8m foundation slab; (2) the modulus of elasticity of the concrete was considered 34500 N/mm² (~C28/35 class); (3) the base shear coefficient for this type of structure and for the above-mentioned region was calculated to be 0.13852 and the seismic loading was applied at the interface between the ground and the superstructure; (4) all superstructure levels were of 3.05 m in height; (5) the underground level height was of 2.8 meters; (6) the loads were determined in accordance with the local norms – a long term 6.245 KN/m² load was considered for the roof slab and a 6.885 KN/m² load for all other levels in terms of long term loading and 11.695 KN/m² in terms of maximum expected loading; (7) the load cases and combinations took into account the long term loads together with seismic action on x and y directions, with 5% eccentricity; (8) the models did not take into account the superstructure “super-resistance” and post-elastic behaviour, as the models were only for determining the expected general behaviour understanding – however, it is expected that such considerations are made in an actual design process (for structural validation); (9) all
models with thermal insulation/XPS considered a 200 mm layer of Styrodur 5000CS material applied beneath the foundation raft and around the outer side of the underground walls; the main property considered for this material within the calculations was its long-term modulus of subgrade reaction of 70000 kN/m³, as per manufacturer indications (available in the product data sheet); (10) a linear static analysis was employed for all models in order to determine building response periods and drifts.

3.3.1. Effective stiffness and site response. In order to create models that consider the building – polystyrene – ground interaction “most” accurately, advanced investigations towards determining precise relations (incl. boundary conditions) between the materials’ properties and their linear/non-linear behaviour subject to different types of loads may be required. This refers to the need for a better understanding of how a TI/XPS layer and its interaction with the general site conditions may influence the ground/subgrade response and other properties/effects that may relate to effective stiffness, damping, etc., while subject to seismic loading. Nevertheless, in a simplified manner, both the polystyrene layer and the subgrade may be modelled using the “Winkler” springs system. This presumes a linear behaviour of the materials and can be relevant in the overall structural behaviour assessment only for limited deformations at geotechnical level. Even so, the influence of the polystyrene in larger strain/deformation conditions may be limited and the overall behaviour is expected to be dictated by the actual local site profile. However, this should be determined by advanced studies of specific local site conditions [10], as establishing appropriate values for the subgrade reaction is crucial in properly modelling any SSI. For the proposed models of this paper, the effective stiffnesses, as values for the area springs used for modelling the SSI, have been determined as follows: (1) the effective subgrade reaction was established by determining the building “active zone” in accordance with NP 112, while considering the mechanical properties of the XPS layer underneath the foundation; (2) the transversal “subgrade reaction” “k_{sh}” was determined with equation “6” [9], based on the width of the raft (B), its length (L) and the actual subgrade reaction (“k_s”); (3) the effective horizontal “ground stiffness” on the underground walls was determined by considering that a force that would induce a Δ_{ground} deformation would also induce an extra Δ_{polystyrene} deformation. Provided a linear behaviour of the materials, this relation is described in equation “3”. This is an “unfavourable scenario” assumption as the influence of the XPS layer on the ground reactions may be smaller and the difference in “overall stiffness” may be dependent on the properties of the ground layer it replaces (which may be ”softer” than the TI material). A more precise relation may be the one in which the difference between the additional displacement caused by the polystyrene is related to the displacement that would have been susceptible for the ground layer it replaces (i.e. equation “4” - the difference between the displacement in the XPS layer and the displacement that would be caused in the layer it replaces, subject to the same applied force), as shown in equation “5”; where “k_{rl}” is the stiffness of the layer replaced by the XPS, “k” the “overall ground initial stiffness/reaction”, either for vertical or horizontal modulus of subgrade reaction, and “k_{pol}” the “stiffness” of the polystyrene. Equation “5” may be used for modulus of subgrade reaction calculation.
However, for determining “\( k_h \)”, the more “unfavourable” equation “3” was used. Knowing the dynamic stiffness of the polystyrene “\( k_{pol} \)” and the “ground stiffness” “\( k_g \)”, and having Hooke’s equation “1”, which describes the relations between pressure “\( \sigma \)”, deformation “\( \Delta \)” and stiffness “\( k \)”, an effective stiffness may be roughly estimated. The influence of the vertical and horizontal interfaces between the different materials (i.e. ground, XPS, concrete) has been neglected in the models, presuming the friction between materials is high enough – however, this should be further investigated in the design process, as it can be expected that in some cases additional relative displacements might occur in the interface plane. The modulus of subgrade reaction “\( k_d \)” for seismic loading was calculated based on a transformation of the modulus of subgrade reaction “\( k_s \)” for static loading, using the previously mentioned modification factor “\( \alpha \)” (as shown in equation “7”).

\[
\sigma = \Delta \cdot k \\
\Delta_{eff} = \Delta_{ground} + \Delta_{pol} \Rightarrow \sigma \cdot k_{eff}^{-1} = \sigma \cdot k_g^{-1} + \sigma \cdot k_{pol}^{-1} \\
k_{eff} = k_{pol} \cdot k_g \cdot (k_{pol} + k_g)^{-1} \\
\Delta_{eff} = \Delta_{ground} + (\Delta_{pol} - \Delta_{rl}) \\
k_{eff} = \frac{k \cdot k_{pol} \cdot k_{rl}}{k_{rl} \cdot k_{pol} - k \cdot k_{pol} + k_{rl} \cdot k} \\
k_{sh} = k_s \cdot \left( 1 + \frac{0.6}{1 + \left( \frac{L}{B} \right)^2} \right)^{-1} \\
k_d = \alpha \cdot k_s
\]

3.3.2. Fixed superstructure model. The general accepted way of design is to consider the underground as a rigid box that moves “together” with the ground. The first model (Model I) was created for the purpose of conducting a preliminary verification of drifts, as a general pre-dimensioning / validation (for this exercise only) criteria for the chosen structure, and therefore only considers the superstructure, which is fixed at the bottom.
The results of the analysis shown a 0.398s building period on x and 0.401s period on y. Drifts verification for the service limit state (SLS), which are the story drifts provided by ETABS multiplied with the story height, were less than the maximum admissible value of 0.01525m – “drSLSa”, meeting therefore the requirements set by P100 on this matter. Also, the ultimate state limit (ULS) drift requirements (for this the structure was modelled using an elasticity modulus of the concrete diminished to half – i.e. 0.5 E_{concrete}) were met for this structural configuration.

Table 3. Model I - Maximum SLS drifts (drSLS_{max}) against allowed values (drSLS_{a})

|        | drSLS_{max} (m) | drSLS_{a} (m) |
|--------|----------------|---------------|
| Story 5 | 0.003479288    | 0.01525       |
| Story 4 | 0.005342456    | 0.01525       |
| Story 3 | 0.007123275    | 0.01525       |
| Story 2 | 0.008245294    | 0.01525       |
| Story 1 | 0.008018831    | 0.01525       |
| G Floor| 0.004632188    | 0.01525       |

Table 4. Model I - Maximum ULS drifts (drULS_{max}) against allowed values (drULS_{a})

|        | drULS_{max} (m) | drULS_{a} (m) |
|--------|----------------|---------------|
| Story 5 | 0.029395609    | 0.07625       |
| Story 4 | 0.045137044    | 0.07625       |
| Story 3 | 0.06022621     | 0.07625       |
| Story 2 | 0.069705859    | 0.07625       |
| Story 1 | 0.06774905     | 0.07625       |
| G Floor| 0.039092681    | 0.07625       |

3.3.3. Models considering the infrastructure. The interaction between the structure and the ground was modelled using area springs with different values, as shown in Tables 7 and 8.
The spring values have been calculated as described in sub-chapter 3.3. Multiple models with the same distribution of area springs have been created to reflect the different scenarios: (1) Model II-A – non-cohesive ground (NCG), without XPS, $\alpha=2.5$; (2) Model II-B – NCG, with XPS, $\alpha=2.5$; (3) Model III-A – NCG, without XPS, $\alpha=5$; (4) Model III-B – NCG, with XPS, $\alpha=5$; (5) Model IV-A – cohesive ground (CG), without XPS, $\alpha=2.5$; (6) Model IV-B – CG, with XPS, $\alpha=2.5$; (7) Model V-A – CG, without XPS, $\alpha=5$; (8) Model V-A – CG, with XPS, $\alpha=5$.

The 3D Etabs Model – infrastructure added.

**Figure 8.**

The 3D Etabs Model – area springs applied at infrastructure level.

**Figure 9.**

Underground springs arrangement - horizontal area springs “$k_{h}(Z)$” on the outer side of the underground walls, horizontal area springs under the foundation raft “$k_{sh}$”, and vertical area springs under the foundation raft “$k_{s}$”. In the proposed models, the horizontal modulus of subgrade reaction associated with the outer side of the underground walls was considered to vary on the vertical and therefore different values were calculated, as shown in Tables 6, 7, and 8. The modulus of subgrade reactions associated to the interface at the bottom side of the foundation raft, either if we refer to “$k_{s}$” or “$k_{sh}$”, were assumed constant on the entire raft surface – however, in actual site conditions, a variation of these values may be expected, and more accurate models should consider this. “$k_{h}(Z)$”, “$k_{s,d}$” and “$k_{sh,d}$” are the modulus of subgrade reactions transformed and estimated using “$\alpha$” coefficients, as an attempt to determine the ground response subject to dynamic / seismic like loading.

For each hypothetical ground conditions, the absolute settlement has been calculated. The results are shown in table 5. This is the most direct consideration from norms and standards point of view regarding the application of various layers underneath the building. For example, the total settlement restriction for concrete-frames structure with brickwork filling is 80mm.

**Figure 10.**
Table 5. Total settlement calculated based on NP112 prescriptions (active zone ~ 13.7m deep).

| Scenario          | Non-cohesive soil scenario, E=27000 kPa | Total settlement Cohesive soil scenario, E=18000 kPa |
|-------------------|----------------------------------------|--------------------------------------------------|
| Without XPS       | 49.50 mm                               | 74.26 mm                                         |
| With 200mm of XPS | 50.90 mm                               | 75.16 mm                                         |

Table 6. Ground stiffness/reaction data

| k₀ (Z), where Z is depth in meters; subgrade reaction (kₛ) & “transverse stiffness” (kₘ₀) | k static (for non-cohesive soil - E=27000 kPa; applied pressure of 167kPa at excavation level) [kN/m³] | k static (for cohesive soil - E=18000 kPa; applied pressure of 167kPa at excavation level) [kN/m³] |
|-------------------------------------|------------------------------------------------------|------------------------------------------------------|
| NO XPS layer                        | WITH XPS                                             | NO XPS layer                                         | WITH XPS |
| kₘ₀ (0.00)                          | 0.00                                                 | 0.00                                                 | 0.00     |
| kₘ₀ (0.25)                          | 2250.00                                              | 2161.31                                             | 1250.00  |
| kₘ₀ (0.75)                          | 6750.00                                              | 6010.10                                             | 3750.00  |
| kₘ₀ (1.25)                          | 11250.00                                             | 9334.68                                            | 6250.00  |
| kₘ₀ (1.75)                          | 15750.00                                             | 12235.33                                           | 8750.00  |
| kₘ₀ (2.25)                          | 20250.00                                             | 14788.26                                           | 11250.00 |
| kₘ₀ (2.75)                          | 24750.00                                             | 17052.48                                           | 13750.00 |
| kₘ₀ (2.80)                          | 25200.00                                             | 17264.89                                           | 14000.00 |
| kₘ₀ (3.00)                          | 27000.00                                             | 18091.20                                           | 15000.00 |
| kₛ                                  | 3373.79                                              | 3281.39                                             | 2249.19  |
| kₘₐ                                 | 2699.03                                              | 2625.10                                             | 1799.35  |

Table 7. Ground dynamic stiffness/reaction data (α=2.5)

| kₘ₀,d (Z), where Z is depth in meters; subgrade reaction (kₛ,d) & “transverse stiffness” (kₘ₀,d) | k dynamic for non-cohesive soil scenario (α=2.5) [kN/ m³] | k dynamic for cohesive soil scenario (α=2.5) [kN/ m³] |
|---------------------------------------------------------------------------------------------|-----------------------------------------------------------|---------------------------------------------------------|
| NO XPS layer (values for MODEL II-A) | WITH XPS (values for MODEL II-B)                          | NO XPS layer (values for MODEL IV-A) | WITH XPS (values for MODEL IV-B) |
| kₘ₀,d (0.00)                                             | 0.00                                              | 0.00                                             | 0.00                     |
| kₘ₀,d (0.25)                                             | 2250.00                                          | 2161.31                                          | 1250.00                |
| kₘ₀,d (0.75)                                             | 6750.00                                          | 6010.10                                          | 3750.00               |
| kₘ₀,d (1.25)                                             | 11250.00                                         | 9334.68                                          | 6250.00               |
| kₘ₀,d (1.75)                                             | 15750.00                                         | 12235.33                                         | 8750.00               |
| kₘ₀,d (2.25)                                             | 20250.00                                         | 14788.26                                         | 11250.00             |
| kₘ₀,d (2.75)                                             | 24750.00                                         | 17052.48                                         | 13750.00             |
| kₘ₀,d (2.80)                                             | 25200.00                                         | 17264.89                                         | 14000.00             |
| kₘ₀,d (3.00)                                             | 27000.00                                         | 18091.20                                         | 15000.00             |
3.3.4. Models considering the infrastructure - results. The results of the analysis are shown in tables 9 and 10, in terms of maximum storey drifts and building period on x and y directions. The analysis is made for service limit state only (SLS).

Table 9. Non-cohesive ground (NCG) conditions, Maximum Drifts, SLS

| Max Drifts | MODEL II-A (non-cohesive soil, α=2.5) | MODEL II-B (non-cohesive soil, α=2.5) | MODEL III-A (non-cohesive soil, α=5) | MODEL III-B (non-cohesive soil, α=5) |
|------------|----------------------------------------|----------------------------------------|--------------------------------------|--------------------------------------|
| St. 5      | 0.02044                                | 0.0210713                              | 0.012126                             | 0.012434                             |
| St. 4      | 0.02230                                | 0.0229345                              | 0.013989                             | 0.014298                             |
| St. 3      | 0.02410                                | 0.0247359                              | 0.015790                             | 0.016109                             |
| St. 2      | 0.02530                                | 0.0259300                              | 0.016984                             | 0.017293                             |
| St. 1      | 0.02527                                | 0.0258991                              | 0.016953                             | 0.017262                             |
| G. F.      | 0.02253                                | 0.0231609                              | 0.014215                             | 0.014524                             |
| $T_x$ SLS (s) | 0.592888                              | 0.600790                               | 0.51001                              | 0.51441                              |
| $T_y$ SLS (s) | 0.847559                               | 0.861342                               | 0.66945                              | 0.67809                              |
Figure 11. Maximum SLS drifts (m) for non-cohesive soil conditions (without polystyrene II-A and III-A, with polystyrene II-B and III-B). Minor influence of XPS layer can be noted for each scenario.

Figure 12. Maximum SLS drifts (m) for cohesive soil conditions (without polystyrene IV-A and V-A, with polystyrene IV-B and V-B). Minor influence of XPS layer can be noted for each scenario.
Table 10. Cohesive ground (CG) conditions, Maximum Drifts, SLS

| Max Drifts | MODEL IV-A (cohesive soil, $\alpha=2.5$) | MODEL IV-B (cohesive soil, $\alpha=2.5$) | MODEL V-A (cohesive soil, $\alpha=5$) | MODEL V-B (cohesive soil, $\alpha=5$) |
|------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| St. 5      | 0.0291004                       | 0.0295431                       | 0.0164494                       | 0.0166759                       |
| St. 4      | 0.0309636                       | 0.0314062                       | 0.0183126                       | 0.0185390                       |
| St. 3      | 0.0327650                       | 0.0332076                       | 0.0201243                       | 0.0203405                       |
| St. 2      | 0.0339591                       | 0.0344017                       | 0.0213081                       | 0.0215345                       |
| St. 1      | 0.0339282                       | 0.0343708                       | 0.0212772                       | 0.0215036                       |
| G. F.      | 0.0311901                       | 0.0316327                       | 0.0185390                       | 0.0187655                       |
| $T_s$,SLS (s) | 0.670003                     | 0.6754640                       | 0.5553380                       | 0.5585260                       |
| $T_y$,SLS (s) | 1.002424                     | 1.0112160                       | 0.7689050                       | 0.7745860                       |

Figure 13. Model II-B drifts (non-cohesive soil conditions with polystyrene) versus Model IV-A drifts (cohesive soil conditions without polystyrene). This suggests that the overall ground conditions have a more important influence on the building response compared to the XPS layer itself (i.e. relatively smaller influence on expected drifts for strong ground with XPS compared to softer ground conditions without XPS).
Figure 14. Model III-B drifts (non-cohesive soil conditions with polystyrene) versus Model V-A drifts (cohesive soil conditions without polystyrene). Similar conclusions as from Figure. 13.

To be noted that the models, periods, and drift values provided are only for comparison purposes between different scenarios and not for structural validation.

4. Considerations from existing studies

Several studies on the matter of usage of TI materials at infrastructure level are available, including studies that cover issues related to the application of such materials in seismic prone areas. The available studies bring into discussion various subjects, as the material behaviour under mechanical loading and, for this, several studies with test results are available. Apart from this, some studies treat the subject of the interface between TI and concrete/ground and suggest that design consideration should be made, for example, against the horizontal sliding possibilities between the TI and blinding concrete during a strong seismic event [6], while there are other studies that prospect even the idea of using the TI layers/boards as a “seismic fuse” [12] during earthquake events. Therefore, it is recommended that the interface between the ground, TI boards, and concrete structures is analysed from multiple perspectives, such as its behaviour during seismic activity and its effects on the building response to seismic action, but also to what the “correct” boundary conditions between different materials interfaces are.

The “Seismic behaviour of buildings founded on thermal insulation layer” study provided an idea on one important aspect and potential risk that comes with inserting flexible layers of thermal insulation between the reinforced concrete foundation plate and levelling concrete on the ground. By doing so, the fundamental period of the structure may be prolonged, because the building on insulation layer oscillates slower as on a firm ground \( T_{\text{isolated}} > T_{\text{nonisolated}} \). The fundamental periods can be additionally increased due to rocking effects which might be a consequence of vertical deformability of the insulation layer. For example, most passive houses are up to two stories high-low rise buildings with short fundamental periods \( T_n < 0.1 \text{ s} \), which could be further elongated by the insertion of a thermal insulation layer and thus moved into the resonance part of the design response spectrum [2].

This emphasises the idea that the design of buildings should consider their interaction with the ground and, in this case, with the thermal insulation layer, in a general model, in order to establish how
this layer might influence the fundamental periods, lateral drifts, etc of buildings. Other studies [13] also suggest that seismic codes should have sections specially dedicated to SSI modelling / calculation.

5. Conclusions
The new requirements for high energy-efficiency buildings lead in certain cases to new demands on the market for finding ways to have a complete thermal envelope, including underneath foundations and around the infrastructure, whenever this may have a serious added value to the energy efficiency of the building and is possible in terms of structural safety. On the other hand, new materials are available on the market and this leads to new design perspectives that should be explored.

For a preliminary understanding of the potential implications of using thermal insulation materials at infrastructure level, an indirect method approach modelling was performed on a hypothetical building as described in sub-chapter 3.3, considering a certain type of XPS material as thermal insulator. The process of thought and incipient considerations presented in relation to this type of material could be extended to other types of materials that might be used as TI at infrastructure level. It should be mentioned that the models covered only some general aspects related to the building expected seismic response (i.e. drifts and periods) in different environments (with and without TI, in cohesive and non-cohesive ground conditions). It does not cover geotechnical aspects regarding damping capabilities or other effects or consequences of high strains/deformations and non-linear response at geotechnical level, which should be a matter of deeper research. Also, the accountability of foundation size, stiffness and building rigidity in the SSI kinematic aspects cannot be properly assessed through indirect methods (i.e. using only area links / springs) without having sufficient experimental data to validate this approach, leading to the conclusion that, in some cases, for a more precise structural validation, a direct SSI method (software with higher modelling options) should be employed, provided again, that sufficient data is available (e.g. physical properties of the environment, materials / elements properties, boundary conditions and interaction between various layers). It has to be mentioned that applying indirect methods can be difficult and can lack rigour due to lack of sufficient guidelines and specifications on how to properly determine the subgrade vertical and horizontal reaction values (to be modelled as links / strings) during an earthquake, as such features of the ground response are different in case of seismic loading, compared to those that characterise static loading. A direct transformation, even if in some papers is provided (e.g. based on considerations arising from the “transient” specific of the seismic loading, some conversions are suggested), available research seems to lack a rigorous explanation on the chosen values of the coefficients that may be used to convert a modulus of subgrade reaction for static loading to a modulus of subgrade reaction for seismic loading (e.g. in certain papers, reference to “specialized literature” is made, without direct reference). In case of direct SSI modelling, the question remains on the capability of the software that is to be used and the understanding of how it performs the calculation of both the ground and structure is essential. As a general comment, not relating only to the application of TI layers underneath buildings, but rather to how SSI modelling is performed overall, further studies and development of precise norms and prescriptions on calculating such SSI (including concerns related to embedment in layers of different types) should favour a better understanding of the approach towards a qualitative design, while also imposing more clear rules, that would more concisely respond to actual circumstances, and better assist buildings designers in their work. In constructing such methodologies for design, employing deeper consideration for specific underground levels behaviour (apart from the embedding conditions) during earthquakes should be made, in order to assess the general behaviour of buildings [14].

The results of the modelling described in subchapter 3.3, with the available data, assumptions (e.g. relatively “high strength” XPS TI, chosen building specifics) and modelling options (e.g. indirect method only for comparison purposes – not structural validation) and choices presented in the current paper lead to the idea that the thermal insulation layer underneath the foundation slab alone brings only relatively small increase (less than 3%) in building period, story drifts, effort distribution and overall base deformations compared to the initial hypothetical site conditions (note: results obtained for SLS verification only). This increase shows to occur whenever the XPS is used in relatively stiff ground
conditions (i.e. on average $E_{\text{ground}} > E_{\text{XPS}}$) and therefore it (the XPS) plays a role in lowering the overall subgrade stiffness of the active zone. However, the opposite is susceptible to occur in case of soft soil conditions, where the XPS may slightly increase the subgrade reaction values, based on its “share” in the overall active zone. Moreover, the general site conditions and ground profile prove to be much more relevant than the TI layer itself for the superstructure response, as shown in Figures 13 and 14. This means that a very soft ground without this type of TI may lead to higher drift values and building periods than a stiff ground with TI.

It can be observed in terms of modulus of subgrade reaction and overall settlement, that the influence of the TI layers is directly related to the size of the active zone – e.g. the same thickness of XPS layers influence in the overall modulus of subgrade reaction value will decrease as the active zone depth increases and it will increase as the active zone depth decreases. Therefore, the usage of such TI ($E \sim 15000$ kPa, $k \sim 70.000$ kPa/m$^3$) is expected to be mostly relevant for buildings whenever the active zone is relatively small and/or characterized by high stiffness soil profiles. Nevertheless, in scenarios where the active zone is relatively small in depth, the exposure to loading of the TI layers can also be expected smaller.

Apart from the NP112 absolute settlements requirements, there are no specific provisions within local technical prescriptions regarding “when and how” such TI materials may be applied at infrastructure level (apart from the overall settlement considerations) and even more, there are no direct prescriptions for SSI analysis that could be used for a straight forward approach; and no reference is made to the buildings “embedding” requirements subject to different stratifications and/or ground profiles that would include such TI (or similar) materials. The only means to calculating such layers seems to be through a definition of such layers as part of the subgrade and inclusion of such in the available methods for soils. In some cases, this leaves a grey area for design choices and creates a certain level of uncertainty and inherent controversies on the possibilities of applying such materials.

Usually, in common practice, the superstructure is modelled separately from the infrastructure, as the latter is considered to move “together” with the ground during seismic activity and SSI analysis is generally neglected. However, the SSI analysis may be extremely relevant in certain cases and the local P100 code recommends such an analysis when SSI effects may be important. Alone, the general design practice does not allow for an “undoubtable” understanding of how the local site conditions and, in this case, the TI layer(s) or any other type of layer inserted at infrastructure level may affect the superstructure response. In the romanian norms there seems to be no exact definition of required threshold limit values for embedment of a building beneath the interface under which it should be “fully” fixed, and sometimes there is a risk that this issue is completely neglected in common design practice.

Extensive research and studies are recommended for a better and more straight forward understanding of the feasibility, necessity and possibilities of applying the various available types of TI layers (or any other type of fill / synthetic fill) underneath buildings and structures within seismic areas. Also, clear technical prescriptions with application guidelines and general acceptance conditions for a more direct and unified design approach employing SSI analysis (including multi layered embedment cases, while also considering the sometimes difficult process of compacting backfill material next to structures) should be in place, as SSI calculations can sometimes prove to be extremely relevant and a more realistic approach (e.g. rigid structure on soft ground, relatively unfavourable ground conditions, etc. [15]) than using the general way (e.g. superstructure fixed at the bottom, infrastructure calculated separately). For this, SSI studies should be based on effective data retrieved (i.e. monitoring of actual buildings for which the geotechnical profile is known in detail) from actual on-site behaviour of buildings, pending various types of embedding conditions, during earthquake events. Since the SSI is very complex in nature, special consideration should be made especially for relatively high-rise buildings on soft soil [16].

As both available studies [17] and existing material data sheets suggest, the available XPS materials on the market seem to have enough compressive strength and good compression-deformation properties, allowing them to be used “underneath” low-level / light buildings at least. Nevertheless, extensive design considerations should be made, and proper direct SSI modelling, with considerations for the interfaces
between layers, is recommendable for assessing site conditions and building embedment “effectiveness” (especially for multi-storey buildings), whenever this may be relevant, pending sufficient site data acquisition and understanding of the specific design concerns (e.g. different seismic regions in Romania, means different design considerations from one site to another).

This paper covers only some limited general aspects regarding the possibilities of using TI layers at infrastructure level (beneath the foundation slab and/or on the exterior of underground walls) in areas exposed to earthquakes and the expected influence of such layers on the superstructure. It does not validate the unequivocal usage of such materials, but only emphasizes some aspects that should be considered in the design process, whenever such TI materials are considered to be used. From the structural safety point of view, the choice of using such materials should be subject to an exhaustive SSI design approach, while addressing post-elastic behaviour concerns as well (not covered by this paper). Also, apart from the XPS (or similar) material’s mechanical & thermal properties and its compliance with overall design prescriptions and requirements (including over longer periods of time), further design attention should be also given to the exposure of subgrade TI materials to other threats, such as water ingestion, pests and/or other aggressive and damaging environments.

As final point, it should be taken into account that, if XPS (or similar) is to be used, additional considerations should be made as, such materials may be characterised by a high carbon footprint / global warming potential. Therefore, other methods and solutions for thermally insulating buildings at foundation level might prove to be a better choice from this perspective alone. [18][19]

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