EVALUATION OF THE STRUCTURAL BEHAVIOR OF FRONT-END LOADER BUCKETS SUBJECTED TO DIGGING FORCE LOADS, USING THE FINITE ELEMENT METHOD

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Abstract: This paper presents the evaluation of the structural behavior of a front-end loader bucket subjected to loads generated by the digging force, using the finite element method. The geometric model of the bucket is developed in the SolidWorks environment, while the numerical analysis is performed using the SolidWorks Simulation module, considering a linear static analysis. The digging forces are determined based on analytical relationships specific to the excavation process and are applied to the bucket structure under representative operating conditions. The distributions of equivalent Von Mises stresses and displacement fields are analyzed for several types of excavated materials. The obtained results allow the identification of critical structural areas and highlight the influence of the excavated material on the stress state, providing useful conclusions for safety assessment and constructive optimization of the bucket.

Keywords: front-end loader, bucket, digging force, finite element method, Von Mises stresses, structural analysis.

1. INTRODUCTION

Front-end loaders equipped with buckets are machines intended for loading and unloading operations involving soil, granular and pulverulent materials, ores, as well as carbonaceous products. The main working tool is the bucket mounted at the front of the machine, which is used for handling bulk materials through machine movement, short-distance transport (from a few meters up to several tens of meters), and unloading into transport vehicles or storage piles. Under certain conditions, front-end loaders may also be used for excavation in low-strength soils, by forming a cutting slice during machine advancement, as well as for leveling works or handling loads [1].

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During excavation, the physical and mechanical properties of the excavated material manifest themselves through the occurrence of resistant forces that oppose the penetration and advancement of the working tool. The magnitude of these forces depends both on the constructive parameters of the bucket (geometry, thicknesses, stiffeners, cutting edges) and on the operating regime (bucket position, attack and clearance angles, penetration depth, and the condition of contact surfaces). The determination of resistant forces can be performed experimentally or analytically, and depending on the nature and state of the material, the excavated slice may exhibit different shapes and failure mechanisms.

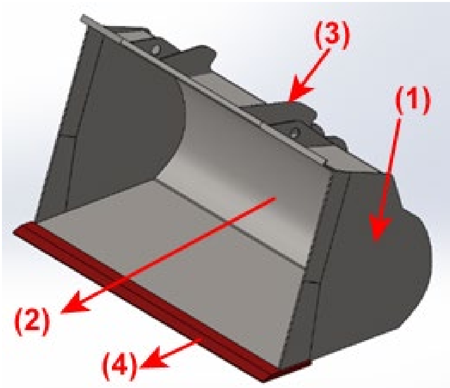
The digging resistance is also influenced by the angles formed between the working tool and the contact surfaces, as well as by the degree of wear of the cutting edges. These aspects lead to significant variations in the loads transmitted to the bucket structure and may generate local stress concentrations in sensitive areas such as cutting edges, stiffening ribs, welded joints, and section transition zones [2–3].

In this context, the present paper aims to evaluate the structural behavior of a front-end loader bucket subjected to loads generated by the digging force, under representative operating conditions. The distributions of equivalent Von Mises stresses and displacements within the bucket structure are analyzed for three distinct types of excavated materials: loose coal, marl, and clayey soil. The study integrates three essential components of engineering design: analytical calculation of digging forces, CAD geometric modeling, and numerical analysis using the finite element method (FEM), with the objective of identifying critical areas and formulating conclusions useful for safety assessment and constructive optimization of the bucket [4–5].

In the specialized literature, the structural analysis of working tools used in excavation machinery has been addressed using both analytical approaches and numerical simulations based on the finite element method. Existing studies highlight the importance of correlating the properties of the excavated material with the geometry of the working tool in order to accurately estimate digging forces and stress states in load-bearing structures [1–4]. FEM analyses are widely employed to identify critical zones, assess durability, and optimize bucket structures; however, many studies consider generalized cases or standardized operating conditions. This justifies the need for comparative studies adapted to different types of excavated materials, as presented in this paper.

2. CONSTRUCTIVE DESCRIPTION OF THE ANALYZED BUCKETS

The bucket subjected to analysis is a welded assembly composed of several steel plates with different thicknesses, arranged in such a way as to ensure adequate stiffness and strength under operating conditions, as shown in Figure 1.



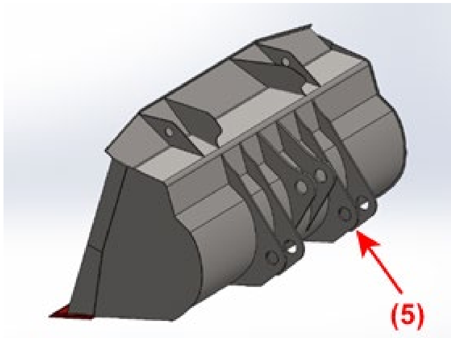


Fig. 1. 3D model of the front-end loader bucket

The structure consists of the following main components:

- Main body, formed by two lateral plates (1) and an inner curved surface (2), designed to facilitate the loading and transport of the excavated material.
- Internal stiffening elements, consisting of welded reinforcements (3) placed on the outer surface of the bucket, arranged both axially and transversely, in order to prevent excessive deformations and to ensure the structural stability of the bucket under service loads.
- Reinforced front edge, equipped with a wear blade (4), which primarily withstands friction and abrasive action of the excavated material, thus contributing to an increased service life of the bucket.
- Mounting flanges (5), provided with holes for pins, which allow the attachment of the bucket to the lifting and handling mechanism of the front-end loader. These components are designed to withstand both static mechanical loads and dynamic loads occurring during loading operations.

This constructive configuration is typical for equipment used in mining applications and earthmoving works, where high wear resistance and structural rigidity are essential for continuous and safe operation. The bucket material is structural steel S355, which provides good resistance to abrasion and ensures adequate structural stability under impact and operational loading conditions.

3. STAGES OF THE ANALYSIS

The analysis of the structural behavior of the front-end loader bucket is carried out in three complementary stages, aiming to achieve a comprehensive understanding of the loading mechanisms and of the manner in which the properties of the excavated materials influence the loads transmitted to the structure. This step-by-step approach allows the correlation of analytical calculations with geometric modeling and numerical analysis based on the finite element method, ensuring the consistency and validity of the obtained results.

3.1 Evaluation of the digging force by analytical methods

The evaluation of the digging force represents a fundamental stage in determining the mechanical loads acting on front-end loader buckets during excavation operations. This force characterizes the effort required to dislodge the material from its natural state and to load it into the bucket, being influenced both by the physical and mechanical properties of the excavated material and by the bucket geometry and operating conditions of the machine.

The analytical methods used for the calculation of the digging force are based on empirical and theoretical relationships established in the specialized literature and technical standards (such as DIN and ISO recommendations or technical specifications provided by equipment manufacturers). These relationships allow a rapid and efficient estimation of the force required for the excavation process and constitute the starting point for the structural dimensioning of the bucket and for defining the loading conditions subsequently applied in the numerical analysis.

The digging force is determined by a set of influencing factors, among which the most significant are the following:

- Properties of the excavated material: The unit weight (γ), cohesion, internal friction angle (ϕ), and the friction coefficient between the material and the cutting edge (μ) directly affect the resistance to cutting and failure of the soil or rock layer. For instance, loose coal exhibits lower cohesion and internal friction angle values compared to marl or clayey soil, which results in lower digging force values.
- Bucket geometry and dimensions: The width of the cutting edge (B) and the penetration depth into the material (h) define the frontal area and the volume of displaced material. An increase in these dimensions leads to a proportional increase in the force required for excavation.
- Operating conditions: The cutting edge attack angle and the working regime influence the interaction mechanism between the bucket and the excavated material, leading to variations in the empirical coefficients used in analytical calculations.

The total digging force can be expressed, in a general form, by the following relationship [3]:

$$F_s = k_m \cdot \gamma \cdot V \cdot \left(1 + \mu \cdot \tan\phi\right) \qquad (1)$$

- F_s – total digging force applied to the bucket [N]
- k_m – empirical coefficient accounting for material compactness and cohesion, adapted for each type of soil or rock
- γ – unit weight of the excavated material [N/m³]
- V – volume of material displaced during a digging cycle[m³]
- μ – the friction coefficient between the excavated material and the cutting edge [−]

- ϕ – internal friction angle of the material [°]

This relationship highlights the fact that the digging force does not depend solely on the mass of the displaced material (through the term $\gamma \cdot V$), but also on the internal resistance characteristics of the material, expressed by the coefficients k_m, μ, and ϕ.

Typical values of the parameters corresponding to the analyzed materials are presented in Table 1.

Table 1. **Typical material properties used in the analytical evaluation**

Material	**Unit weight γ [kN/m³]**	**Digging pressure p_m [kPa]**	**Friction coefficient μ**	**Internal friction angle ϕ [°]**	**Material coefficient k_m (estimated)**
Loose coal	8 – 12	50 – 80	0.4	20 – 25	1.2 – 1.5
Marl	15 – 18	120 – 180	0.5	30 – 35	2.0 – 2.5
Wet clayey soil	18 – 21	200 – 350	0.6	35 – 40	2.5 – 3.0

The volume of displaced material is approximated as the product of the frontal cutting area A and the penetration length L (or penetration depth h):

$$V = B \cdot h \tag{2}$$

where:

- B – bucket width (cutting edge width) [m]
- h – penetration depth into the material [m]

For simplified analytical calculations, a unit length of 1 m in the direction of machine movement is considered.

The evaluation of the digging force using analytical methods is indispensable because it:

- provides a rapid reference basis for estimating structural loads without the need for complex numerical simulations;
- allows the calibration and validation of numerical models through comparison with theoretical or empirical results;
- contributes to the optimization of front-end loader design by avoiding both over-dimensioning and under-dimensioning of the bucket structure.

Therefore, this stage represents the first step in the integrated analysis of bucket structural behavior and is essential for the correct definition of loading conditions applied in the subsequent numerical modeling phase.

3.2 Numerical Modeling and Structural Analysis Using the Finite Element Method

Based on the digging force values determined analytically in the previous stage, a numerical analysis of the structural behavior of the front-end loader bucket was performed using the finite element method. The three-dimensional geometric model of the bucket was developed in the SolidWorks environment **[5],** while the structural analysis was carried out using the SolidWorks Simulation module **[6–7],** assuming a linear elastic material behavior.

The finite element method is widely used in the analysis of load-bearing structures of construction and excavation machinery due to its ability to accurately highlight stress distributions, displacement fields, and zones with high stress concentrations [5, 8]. In the present study, the geometric model of the bucket was discretized into solid finite elements using a tetrahedral mesh, suitable for the complex geometry of the structure and for areas with pronounced geometric variations.

The bucket material was considered to be structural steel, characterized by the elastic modulus and Poisson's ratio corresponding to the material grade commonly used in the construction of heavy machinery working tools. The boundary conditions were defined so as to reproduce the real attachment conditions of the bucket to the loader arms, by constraining the displacements in the articulation and mounting regions. The analytically calculated digging forces were applied to the active cutting edge of the bucket and uniformly distributed over the contact surface with the excavated material, as shown in Figure 2.

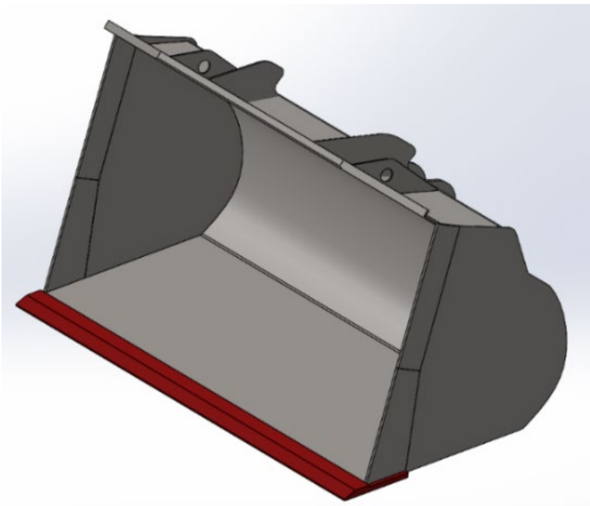


Fig. 2. Geometric model of the bucket

The numerical analysis was performed under static loading conditions, aiming to determine the distribution of equivalent Von Mises stresses and displacement fields. This type of analysis is appropriate for evaluating the stress state under quasi-static operating conditions and is widely used in design and verification studies of structures subjected to slowly varying or moderately variable loads [1,4].

For each of the three analyzed excavated materials (loose coal, marl, and wet clayey soil), distinct loading cases were defined, corresponding to different values of the digging force. The obtained results allow a direct comparison of the stress state and maximum displacements within the bucket structure, highlighting the influence of the excavated material properties on the overall structural behavior.

For the FEM analysis, the bucket geometry was discretized using tetrahedral finite elements, a four-node solid element type well suited for complex three-dimensional geometries, such as welded bucket structures. Tetrahedral discretization enables accurate adaptation to curved surfaces and small-radius corners, ensuring reliable numerical results.

Figure 3 illustrates the discretized bucket geometry, highlighting the tetrahedral finite element mesh, whose density varies depending on the area of interest. Critical zones are meshed more finely in order to improve the accuracy of stress gradient evaluation.

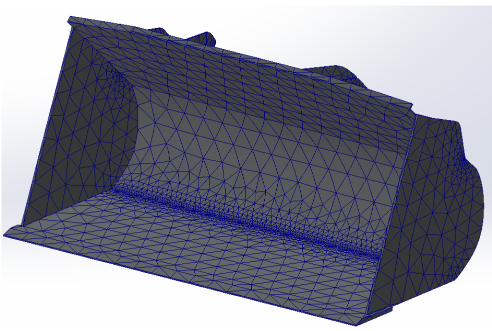


Fig. 3. Discretized bucket geometry

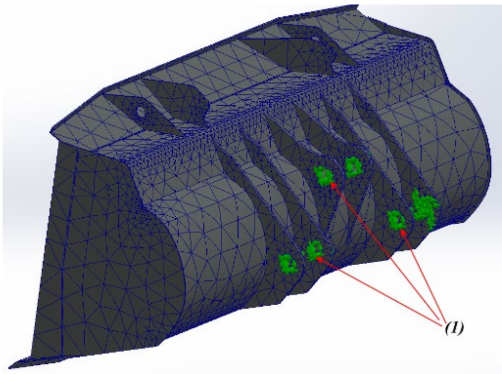


Fig. 4. Boundary conditions applied at the mounting flanges

The quality of the finite element mesh represents a key factor in the accuracy of the results. For the analyzed bucket, an element size was selected to ensure a balance between computational accuracy and calculation time. Areas subjected to high stress levels (corners, welded joints, and wear blades) were discretized using finer elements to correctly capture high stress gradients.

Additionally, boundary conditions were defined at the mounting flanges in order to simulate the rigid connection between the bucket and the machine mechanism, as shown in Figure 4.

3.3 Determination of Equivalent Stresses and Displacement Analysis

Equivalent Von Mises stresses were calculated for each loading case, allowing the evaluation of the stress level relative to the strength limits of the material. At the same time, maximum displacements were analyzed in order to assess their potential influence on the structural functionality of the bucket.

The digging force was evaluated analytically in accordance with relationships

(1) and (2) and the values presented in Table 1, and subsequently applied as distributed loads on the frontal surface of the bucket, in the region of the wear blade.

For the numerical calculations, the following geometric parameters of the bucket were considered:

✓ Bucket width: B = 3.421 m

✓ Bucket depth (frontal height): h = 1.084 m

✓ Cutting edge thickness (frontal surface): $g_{(c)}$ = 10 mm

By integrating analytical and numerical approaches, this case study provides a rigorous evaluation of the critical parameters involved in the design and optimization of front-end loader buckets. The obtained results contribute to the establishment of appropriate dimensioning criteria and material selection guidelines, with a direct impact on the operational performance and safety of mining and earthmoving equipment.

The calculation results are summarized in Table 2.

Table 2. **Distributed digging forces applied on the frontal surface of the bucket**

Material	**Average pressure, p_m [kN/m^2]**	**Total digging force F_s [kN]**
Loose coal	65	241.15
Marl	150	556.50
Wet clayey soil	275	1020.25

Equivalent Von Mises stresses are calculated for each loading case, allowing the evaluation of the stress level relative to the strength limits of the material. In addition, the maximum displacements are analyzed in order to assess their influence on the functionality and service life of the bucket structure.

The results of the static structural analysis for excavation in different materials are presented in Tables 3, 4, and 5.

Table 3. **Structural analysis results for excavation in loose coal**

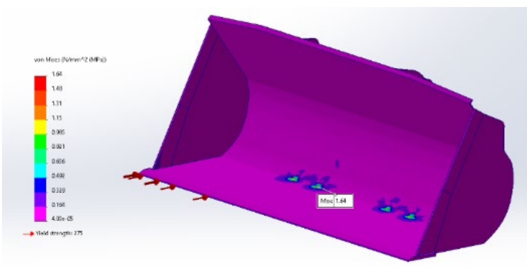
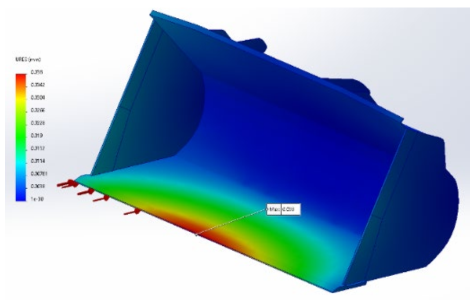
<table>
<tr><td colspan="2">Structural analysis results for excavation in loose coal
for average digging pressure: p_m = 65 kN/m²</td></tr>
<tr><td>Equivalent Von Mises stress,
$\sigma_{(VM,\ max)}$=1.64 [N/mm^2]</td><td>Maximum displacement,
u_{max}=0.038 [mm]</td></tr>
<tr><td></td><td></td></tr>
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Table 4. **Structural analysis results for excavation in marl**

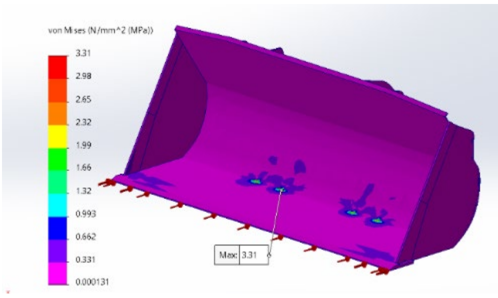
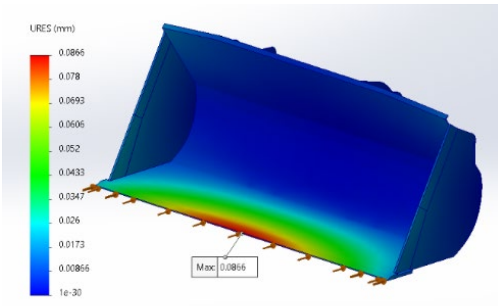
<table>
<tr><td colspan="2">Structural analysis results for excavation in marl
for average digging pressure: p_m = 150 kN/m²</td></tr>
<tr><td>Equivalent Von Mises stress,
$\sigma(_{VM,\ max})$ = 3.31 [N/mm^2]</td><td>Maximum displacement,
u_{max} =0.0866 [mm]</td></tr>
<tr><td>
</td><td>
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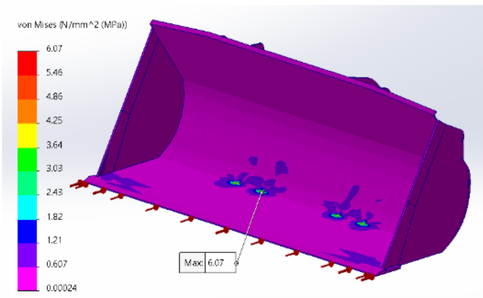
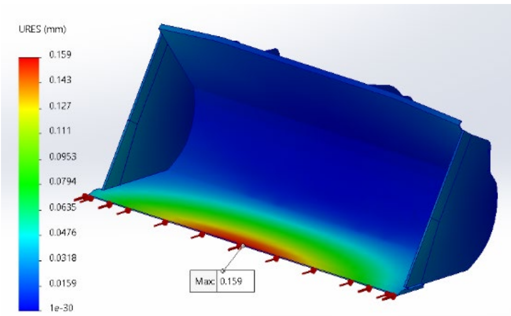
Table 5. **Structural analysis results for excavation in clayey soil**

<table>
<tr><td colspan="2">Structural analysis results for excavation in clayey soil
for average digging pressure: p_m = 275 kN/m²</td></tr>
<tr><td>Equivalent Von Mises stress,
$\sigma(_{VM,\ max})$ =3.31 [N/mm^2]</td><td>Maximum displacement,
u_{max} =0.159 [mm]</td></tr>
<tr><td>
</td><td>
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3.4 Analysis of Stresses and Deformations in the Bucket

A realistic loading scenario corresponding to the frontal loading direction of the front-end loader bucket during the excavation process was considered and analyzed. Following the numerical simulations, the resulting values of stresses and displacements were obtained and are summarized in Table 6.

Table 6. **Stress–displacement values obtained from static analysis**

Material	Average pressure p_m [kN/m²]	Maximum stress $\sigma_{(VM, max)}$ [N/mm²]	Maximum displacement u_{max} [mm]
Loose coal	65	1.64	0.038
Marl	150	3.31	0.0866
Clayey soil	275	3.31	0.159

4. CONCLUSIONS

Based on the performed analysis, the following conclusions can be drawn.

1. Stress distribution

- The maximum equivalent stresses are directly proportional to the pressure applied on the bucket, which is an expected result considering the significant increase in pressure from loose coal to clayey soil, figure 5
- The identical maximum stress values obtained for marl and clayey soil (3.31 N/mm²) indicate that the bucket geometry and loading conditions generate similar critical zones, suggesting that the elastic limit is approached in the same structural regions.
- The stress distribution obtained from the FEM analysis (although not illustrated here) typically shows stress concentration areas located around welded joints, sharp corners, and at the contact region between the cutting edge and the excavated material.
- In the case of loose coal excavation, the stress levels are significantly lower (approximately half of those obtained for the other materials), reflecting the reduced loading conditions associated with the lower applied pressure.

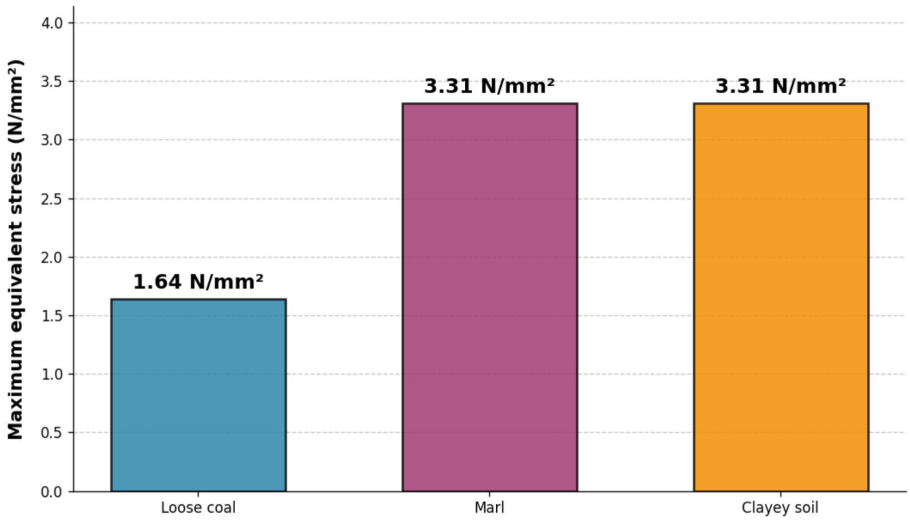

Fig. 5. Maximum equivalent stress in the front-end loader bucket

Figure 6 confirms the increasing trend of structural deformations with increasing excavation pressure.

- For loose coal, the maximum displacement is very small (0.038 mm), confirming the high stiffness of the structure under these loading conditions.
- For marl, the displacement nearly doubles compared to loose coal (0.0866 mm).
- For clayey soil, the displacement increases almost four times relative to loose coal (0.159 mm). This increase highlights the importance of displacement verification in order to prevent adverse effects on the operational functionality and long-term durability of the bucket, especially under high loading conditions.

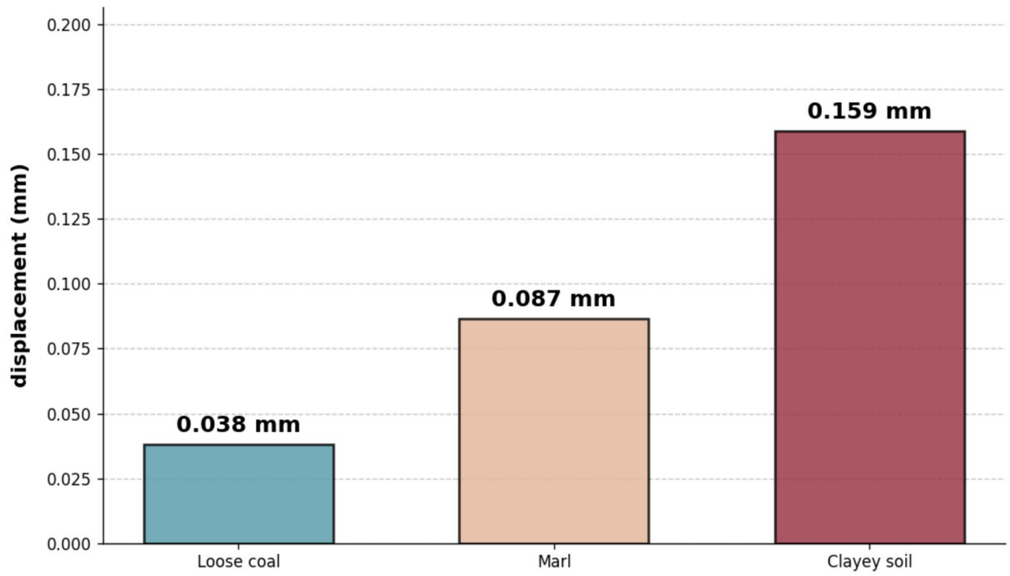

Fig. 6. Maximum displacement in the front-end loader bucket

Final remarks

- Harder and more compact excavated materials generate higher stress and deformation levels in bucket structures, requiring appropriate material selection and constructive solutions.
- The design of front-end loader buckets must consider not only strength limits (stress criteria), but also stiffness limits (deformation criteria), in order to ensure safe operation and long-term durability under real working conditions.

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