Finite element modeling and comparative mechanical analysis of several hoeing tools

Huajie Shen (shenhuajie@fjut.edu.cn)
Fujian University of Technology
Kangkang Zhang
Southwest Forestry University
Kaiqing Shao
Southwest Forestry University
Donghai Huang
Fujian University of Technology
Caiping Lian
Fujian University of Technology
Fengwu Zhang
Sanming University
Yuan Miao
Fujian University of Technology

Research Article

Keywords: hoeing tools,mechanical property,ANSYS workbench,finite element method,synthesized analysis

Posted Date: January 10th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-3841998/v1

Additional Declarations: No competing interests reported.

Abstract

To investigate the material selection basis of hoeing tools, the finite element software ANSYS Workbench was used to compare the material mechanical properties of several typical hoeing tools. Herein, ash wood (*Fraxinus chinensis Roxb.*), beech wood (*Zelkova schneideriana Hand-Mazz*), fir wood (*Cunninghamia lanceolata (Lamb.*) *Hook.*), oak wood *(Cyclobalanopsis glauca (Thunb.) Oerst.*), and locust wood (*Sophora japonica (L.)*) were selected for the hoe handles, and manganese 13 steel, type 45 steel, and spring steel were selected for the cutterhead. The corresponding finite element model was established by Solidworks software, and the force of the hoe tool under general working conditions was presented by ANSYS Workbench simulation, and then the dynamic performance of different materials was analyzed and compared by the comprehensive scoring method. The results of hoeing effect, hoe shank strength and cutter head strength show that the hoeing tool using spring steel as cutter head has higher strength, the hoeing tool using ash wood, beech wood, and Robinia wood as hoe shanks is better than that of zelkova wood and fir wood, and the choice of the material combination of "beech wood shanks + spring steel cutterhead" enables the hoeing tool to realize the best mechanical properties.

Introduction

The hoe is a representative item of China's long history of farming culture and is commonly used because of its simplicity, practicality and applicability. As an important tool for agricultural production, the hoe plays a vital role in agricultural development. Although the mechanization and automation of agriculture has become a trend, traditional hoes still cannot be completely replaced in the next few decades[illegible].Although more and more metal hoe handles have appeared in production and circulation in recent years, wood is still the main material for hoe handles. Due to the differences in the distribution of raw materials and different lifestyles, the types of hoe tools vary from one ethnic group to another and from one region to another. For example, in the north there are more locust trees[1], and local people generally use acacia wood to make hoe handles. On the contrary, beech trees are more abundant in the south[3], and hoe handles made of beech wood are more common. In addition, fir wood, ash wood, rosewood, and oak wood are often used to make hoe handles.

To explore the work efficiency of hoeing tools with different materials and different joining methods, and to compare the differences in the selection habits of hoeing tools in different ethnic groups or different regions, this paper takes the mechanical properties of two important parts, namely, wooden hoe handle and blade head, as the entry point, and selects several common hoeing materials on the market to compare the mechanical properties of several hoeing tool materials. At present, there are two main ways to analyze the mechanical properties of the tool structure: one is to carry out physical test tests on the tool; the other is to use numerical methods to carry out computational analysis, such as the finite element method (FEM) [3][5], and the other is to analyze the mechanical properties of the tool.

The FEM is widely used in evaluating the mechanical properties of tools, for example, LiDai in 2007 used the FEM to study the structural mechanics of sofa frames[6]; Ali KASAL in 2010 used the FEM to determine the strength of various sofa frames[7]; Jerzy SMARDZEWSKI in 2013 used the finite element method to study the structure of upholstered furniture with All joint stiffness was studied [8]; Lorraine CHENG in 2019 used SOLIDWORKS SIMULATION to analyze the mechanical properties of deformed furniture structures by finite element method [9]. Therefore, the FEM can theoretically analyze the experiments under ideal circumstances, and its scientific validity has been recognized by a wide range of scholars.

Here, the FEM analysis is used to synthesize the effect of hoeing, the strength of hoe handle and the strength of cutter head using the traditional hoe as a prototype, and to compare the mechanical properties of several hoe materials, to provide theoretical references for people's future selection of hoes as well as scholars engaged in the research of agricultural implements.

Material and Methods

Material selection and its physical and mechanical performance parameters

As shown in **Fig. 1**, the typical components of a hoe are the cutterhead, the embolus, and the handle. One end of the hoe handle is usually cylindrical, and the other end is inserted into the hole reserved for the cutterhead by means of a mortise and tenon joint. One end of the cutterhead is open to realize the "hoeing" or "chopping" function of the hoe, and the other end is either pre-drilled for mortise and tenon jointing with the hoe handle, or set into the shape required for welding with the hoe handle. The embolus is usually wedge-shaped and is inserted in a flexible connection into the gap between the hoe handle and the cutterhead to strengthen the joint between the hoe handle and the cutterhead. If the hoe handle and cutterhead are joined by welding, the hoe does not have an embolus. Herein, the cutterhead and hoe handle were selected from materials commonly used on the market: 3 types of manganese 13 steel, type 45 stee (common carbon structural steel) and spring steel were selected for the cutterhead. The hoe handles and embolus were made of ash wood, beech wood, fir wood, oak wood, and locust wood. Both hoe handles and embolus were selected consistently during the analysis.

The physic-mechanical properties of the materials in question were obtained from relevant materials and research results, as shown in **Tables 1** and **Tables 2** [10]0[14], and include the modulus of elasticity(Modulus of elasticity on the parallelepiped, E_L; Modulus of elasticity in the horizontal radial direction, E_R; Modulus of elasticity in the horizontal chord upward, M_T), shear modulus of elasticity(Modulus of shear elasticity on the radial surface of the parallel grain, G_{LT}; Modulus of shear elasticity on the parabolic chord surface, G_{LR}; Modulus of shear elasticity in the horizontal plane, G_{TR}), and Poisson's ratio (T-Direction Pressure Strain/R-Direction Extended Strain, $\mu_{RT;}$ R-Direction Pressure Strain/L-Direction Extended Strain, $\mu_{RL;}$ T-Direction Pressure Strain/L-Direction Extended Strain, $\mu_{TL;}$). Their water content was all taken as 12%. Furthermore, the density, modulus of elasticity and Poisson's ratio of the soil used for simulation were all chosen to be 1.330 g/cm3 for 4.54 MPa and 0.410, respectively[15].

Table 1 The physical and mechanical property parameter value of the material selected for the hoe handle

Tree species	Density (g/cm^3)	E_L (MPa)	E_R (MPa)	E_T (MPa)	G_{LT} (MPa)	G_{LR} (MPa)	G_{TR} (MPa)	μ_{RT}	μ_{LR}	μ_{LT}	Bending strength(MPa)	Compressive strength(MPa)
Ash	0.670	15790	1516	827	896	1310	269	0.71	0.46	0.51	112	49
Beech	0.750	13700	2240	1140	1060	1610	460	0.75	0.45	0.51	128	48
Fir	0.390	11583	896	496	690	758	39	0.43	0.37	0.47	75	38
Oak	0.705	16285	1715	880	953	1482	331	0.72	0.44	0.52	142	65
Locust	0.780	12753	1342	690	852	1354	315	0.73	0.47	0.51	124	53

Table 2 The physical and mechanical properties parameter value of the material selected for the toolhead

Materials	Density (g/cm^3)	Modulus of elasticity (MPa)	Poisson's ratio	Maximum strength (MPa)	yield strength (MPa)
Manganese 13 steel	7.791	2.1×10^5	0.3	736	440
Type 45 stee	7.850	2.09×10^5	0.269	600	355
Spring steel	7.810	2.06×10^5	0.285	1765	1570

Finite element simulation

Firstly, the 3D model of the hoe was modeled by Solidworks software. Then the boundary conditions of the hoe in general working conditions were obtained through experiments. A camera was used to shoot the complete cycle of the hoe's work, and the instantaneous velocity at the moment of the hoe's contact with the ground was measured, and then the model was imported into the finite element software ANSYS Workbench, and the material properties and attribute values were set up in accordance with the data in Table 1 and Table 2. 15 types material property settings are combined as "Ash Wood + Manganese 13 Steel", "Ash Wood + Type 45 Steel", "Ash Wood + Spring Steel", "Beech Wood + Manganese 13 Steel", "Beech Wood + Type 45 Steel ", "Beech Wood + Spring Steel", "Fir Wood + Manganese 13 Steel", "Fir Wood + Type 45 Steel", "Fir Wood + Spring Steel", " Oak Wood + Manganese 13 Steel", "Oak Wood + Type 45 Steel", "Oak Wood + Spring Steel"," Locust Wood + Manganese 13 Steel", "Locust Wood + Type 45 Steel", "Locust Wood + Spring Steel". After several simulation tests to find out the boundary conditions that satisfy with the actual situation. Finally, finite element simulation is performed to analyze and compare the results.

Mechanical analysis

Force analysis of hoeing tools

As shown in **Fig. 2**, the user usually holds the hoe with two hands when working with the hoe, but since the swing of the back hand (distal blade end) is small and varies from person to person, the contact point of the back hand is regarded as a fixed point in the analysis of the boundary conditions of the hoe.

During operation, the front hand contact point (near the end of the cutter head) is the force application point, and the force F_1 perpendicular to the hoe handle downward is applied to make the hoe move; the force provided by the back hand contact point can be simplified into F_x and F_y according to the horizontal and vertical directions, respectively. The force only provides the role of supporting the hoe to make the hoe rotate around the point counterclockwise until it impacts on the soil. When contacting the ground soil, the cutter head is subjected to the reaction force F_2 given by the soil to the hoe, and the force analysis is shown in **Fig. 3**.

Certification

To verify whether the components of the hoe are in a safe state when the hoe is subjected to force, the structural strength of the material-the allowable stress of the material-needs to be considered, which refers to the ability of the material to resist the stress applied by the outside world without damage[16]. The materials used in hoeing tools are generally wood and steel, and the permissible stress of the two are calculated according to equation (1) and equation (2) respectively:

$$[\sigma] = \sigma_{12} \bullet K \qquad (1)$$

Where, $[\sigma]$ is the allowable stress value of wood under the condition of 12% moisture content, MPa; σ_{12} is the average value of wood strength under the condition of 12% moisture content, MPa; K is the wood discount factor, due to the need for high-frequency impacts during the operation of hoeing, the hoe handle processing is generally processed through the shade drying treatment in order to improve the discount factor, for safety reasons, the discount factor of the wood for the compressive strength of paracord is 0.75, the flexural strength is 0.45, and the shear strength is 0.55. In equation (2): $[\sigma]$ is the allowable stress of the material, σs is the material yield limit, n is the material yield limit, and the yield strength of the material is 0.55. Flexural strength of 0.45, shear strength of 0.55.

$$[\sigma] = \frac{\sigma s}{n} \qquad (2)$$

Where, $[\sigma]$ is the allowable stress of the material, σ_s is the yield limit of the material, n is the material safety factor. Generally, the safety factor of steel is taken as 1.8.

The permissible stress values of various materials can be derived from Table 1, Table 2, Equation (1) and Equation (2): 36.75 MPa for ash wood, 36 MPa for beech wood, 28.5 MPa for fir wood, 48.75 MPa for oak wood, 39.75 MPa for locust wood; 244.44 MPa for manganese 13 steel, 197.22 MPa for type 45 steel and 872.22 MPa for spring steel, respectively.

Results and discussion

Finite element meshing

The number of grid division will directly affect the calculation data accuracy and calculation scale size. Here, it is necessary to reasonably divide the grid under the condition of ensuring the calculation accuracy and calculation time, and stop refining the grid when the calculation results reach a stable value[17]. For the model structure, the hoe selects tetrahedral solid unit to divide the grid, to get better calculation results, control the overall unit size of 10mm, and refine the grid at the blade of the cutter head and the cutter head contacting the hoe handle with 1mm units, and the rest of the contact with 5mm units for the refinement of the grid. The soil is selected to be meshed with hexahedral solid units, controlling the overall unit to be 20mm[18][20]. Considering the friction between the components of the hoeing tool, to make the force between the components of the hoeing tool more accurate, the contact cells use the algorithm of augmented Lagrangian to enhance the contact between the surfaces and limit the penetration [21]. According to the mesh division conditions, after the mesh division, the whole hoeing tool model has 7196 nodes and 27095 cells, and the soil model has 54621 nodes and 50000 cells, which total 61817 nodes and 77095 cells.

Stress analysis of different hoeing tools

Stress is the set of distributed internal forces at a point on the cross-section[22], and by analyzing the magnitude of the stress value and comparing it with the permissible stress, it can be known whether the strength of the structure meets the conditions. Firstly, the boundary conditions for using the hoe are set up, and to facilitate the setting of boundary conditions, a tiny circular hole is set up at the backhand contact point, and a rotary connecting vice is set up on this tiny circular hole. In the forehand contact point set the size of the force F1 for

15N, where F1 is a continuous constant force (i.e., in the whole hoe impact on the soil process continues to apply and the size of the constant), while the actual work is applied to the variable force (i.e., in the whole process of applying the force is not necessarily sustained and the size of the uncertainty), and the size of the bad judgment and vary from person to person, but only need to be the last in the moment of the hoe contact with the ground moment of the instantaneous speed and the real situation. However, it is only necessary that the instantaneous velocity at the final moment when the hoe touches the ground is basically the same as in the real situation to complete the simulation, so the application of a constant force of F1 of 15N does not affect the experimental results. Since the hoe mainly relies on the assistance of gravity during operation, gravity cannot be ignored, but since each hoe has the same model (same volume) and uses different materials (different densities), the mass of each hoe is not equal, and if the vertical downward standard earth gravity acceleration g is added directly in the vertical direction, it will result in unequal gravitational work done in each group of experiments. To eliminate the effect of unequal gravitational work, the tests were conducted with an equal constant force applied to the cutter head of each hoeing tool as an approximate substitute for gravity, with a magnitude of 10 N. Fixed constraints were added to the bottom surface of the soil.

The LS-DYNA module in the finite element software ANSYS Workbench can dynamically display the impact process of the hoe from falling to contacting the soil and then rebounding, and it can also be combined with the buttons in the animation control area, which can dynamically display the process of stress change of the cutterhead edge at different moments during the impact process [22]. Figure 4 shows the whole process of the cutter head stress reaches its maximum when the stress cloud diagram, from these cloud diagrams can be seen that different materials in the impact process of the stress peak at different points in time, this phenomenon is understandable, because the test is applied to the force is equal, but each hoe using different materials, its density is not equal, in the model of the same (volume is the same) in the case of the mass of the different, the more lightweight hoe will produce The lighter the hoe, the greater the acceleration and the shorter the time taken to impact the soil, but this does not affect the results of the test because the work done by each hoe with the applied force is equal (i.e., the energy input is equal).

As shown in Fig. 4, for statistical purposes, from top to bottom and from left to right, the corresponding drawings are labeled as A1, A2, A3, B1, B2, B3, C1, C2, C3, D1, D2, D3, E1, E2, E3,which correspond to the following: "Ash Wood + Manganese 13 Steel", "Ash Wood + Type 45 Steel", "Ash Wood + Spring Steel", "Beech Wood + Manganese 13 Steel", "Beech Wood + Type 45 Steel ", "Beech Wood + Spring Steel", "Fir Wood + Manganese 13 Steel", "Fir Wood + Type 45 Steel", "Fir Wood + Spring Steel", " Oak Wood + Manganese 13 Steel", "Oak Wood + Type 45 Steel", "Oak Wood + Spring Steel"," Locust Wood + Manganese 13 Steel", "Locust Wood + Type 45 Steel", "Locust Wood + Spring Steel". As can be seen from the simulation results (Fig. 4), the highest stresses in the hoeing tools of all materials during the impact on the soil occurred on the upper end head of the cutter head and on the cutting edge of the cutter head in contact with the soil. Among them, the stresses of using spring steel as the cutter head are small, which are 95.14 MPa for A3, 51.81 MPa for B3, 78.27 MPa for C3, 113.54 MPa for D3 and 160.01 MPa for E3, and the smallest one is that of "cedar wood + spring steel" (51.81 MPa).

Figure 5 shows the structural stress map of the hoe shank and peg when the stress of the hoe tool reaches the maximum in the process of impacting the soil, and its arrangement is consistent with all the structural stress maps in Fig. 4. As shown in Fig. 5, during the impact of the hoe tool on the soil, the parts of the hoe shank and peg where the maximum stress occurred were at the contact between the hoe shank and the cutter head and at the contact point of the back hand, with the contact between the hoe shank and the cutter head being the main point. The results showed that the material combination with the highest stress value was "ash wood + manganese 13 steel" (41.05 MPa), and the smallest was "fir wood + spring steel" (15.99 MPa).

Analysis of soil deformation on impact with hoe tools of different materials

To evaluate the functional effect of the hoe, the depth of its impact on the soil can be used as an intuitive indicator, under the same boundary conditions, the depth of the impact on the soil of hoes of different materials is not the same. Each group of test external force on the hoe work is equal (i.e., the initial energy is the same), but due to the different properties of the material, the energy lost in the energy transfer process is also different[24], the greater the deformation of the soil, it means that the hoe in the energy transfer process of the loss of energy is less, indicating that the hoe work efficiency is better, and vice versa, the worse. Figure 6 shows the maximum value of soil deformation in the process of hoe impacting the soil. As shown in Fig. 6, the soil deformation ranged from 18 mm to 32 mm, and the hoe tools using ash and beech as the hoe handles obviously had a greater working depth, while those using cedar were smaller. The material combination with the largest working depth was "Ash Wood + Type 45 Steel" (31.93 mm), and the smallest was "Locust Wood + Spring Steel" (18.31 mm), while the maximum value of soil impact for hoes made of other materials was generally centered around 30 mm.

Discussion

Taking the traditional hoe as a prototype, the material mechanical properties of several commonly used hoes were compared through the finite element analysis software ANSYS Workbench. The hoe full structure stress to reach the maximum moment of stress, wood structure stress to reach the maximum moment of stress and the maximum deformation of the soil for simulation analysis, the results show that: in the same boundary conditions, different materials of the hoe in the impact of the soil produced by the various structures of the stress are not the same, the strength is inconsistent, so cannot be evaluated through the size of the intuitive stress of the hoe material performance.

The permissible stress of the material as a measure of the strength of the material as the main indicators, the structure of the maximum stress to withstand divided by the permissible stress of the material, you can get the material in a certain boundary conditions of the structure of the maximum stress and the permissible stress of the material of the ratio of the ratio of the smaller the value, it is shown that the structure of the material under the less likely to be destroyed; on the contrary, the more likely to be destroyed. By comparing the ratio of the maximum structural stress to the allowable stress of each material, the strength of the structure can be evaluated. The maximum structural stress of the hoe and the maximum structural stress of the wood in the 12 combinations were divided by the permissible stress of the corresponding materials, and the results are shown in Table 3.

Table 3
Finite element analysis results and scoring results

Number	Maximum steel stress /MPa	Maximum wood stress /MPa	Maximum soil deformation /mm	Maximum stress/allowable stress in steel	Maximum stress/allowable stress in wood	synthesized assessment
A1	203.89	41.05	30.58	0.83411	1.11701	1.16
A2	89.24	22.82	31.93	0.45249	0.62095	2.43
A3	95.14	23.19	30.30	0.10908	0.63102	2.62
B1	227.24	30.33	31.49	0.92964	0.84250	1.58
B2	141.74	27.44	31.78	0.71869	0.76222	1.93
B3	51.81	30.66	28.56	0.05940	0.85167	2.18
C1	105.00	23.86	26.26	0.42955	0.83719	1.68
C2	216.71	23.47	25.21	1.09882	0.85860	0.93
C3	78.27	15.99	25.17	0.08974	0.56105	2.38
D1	64.68	24.48	28.37	0.26460	0.50215	2.54
D2	191.43	29.40	27.20	0.97064	0.60308	1.61
D3	113.54	27.46	30.76	0.13017	0.56328	2.75
E1	106.14	23.20	29.82	0.43422	0.58365	2.35
E2	74.65	27.64	30.29	0.37851	0.69535	2.26
E3	160.01	21.46	18.31	0.18345	0.53987	1.82

It is generally recognized that the performance of a good hoeing implement is such that it can work at a deeper depth with the same external force, in other words, it can save more effort for the same amount of work. At the same time, the hoe itself needs to meet a certain strength. Therefore, the evaluation of the performance of a hoeing tool is a multi-indicator test, which needs to be scored comprehensively. Comprehensive scoring method is a method of scoring, combining multiple indicators into a single indicator (score), using the score of each test to evaluate the results of this test, and using the score of each number of experiments as a method of analyzing the data[25]. In this test, the three indicators of soil deformation is the greater the better, the ratio of the steel structure to the permitted stress and the ratio of the wood structure to the permitted stress is the smaller the better, and the scoring criterion quotes the composite indicator "degree of affiliation", i.e., indicator degree of affiliation = (indicator value-indicator minimum value)/(indicator maximum value-indicator minimum value)[26]. The results of the 12 tests were comprehensively scored, and the scoring criteria were calculated according to the formula (3), and the results were included in Table 3.

$$W=\frac{X-X_{\min}}{X_{\max}-X_{\min}}+\left(1-\frac{Y-Y_{\min}}{Y_{\max}-Y_{\min}}\right)+\left(1-\frac{Z-Z_{\min}}{Z_{\max}-Z_{\min}}\right) \qquad (3)$$

Where, W is the scoring value; X is the soil deformation value of each group of tests, X_{max} is the maximum value of soil deformation in 12 groups of tests, X_{min} is the minimum value of soil deformation in 12 groups of tests; Y is the ratio of steel structure and permissible stress in each group of tests, Y_{max} is the maximum value of steel structure and permissible stress in 12 groups of tests, Y_{min} is the minimum value of steel structure and permissible stress in 12 groups of tests. Z is the ratio of wood structure to allowable stress in each group of tests, Z_{max} is the maximum value of the ratio of wood structure to allowable stress in 12 groups of tests, and Z_{min} is the minimum value of the ratio of wood structure to allowable stress in 12 groups of tests.

The composite scores of each hoe tool are shown in Fig. 7. As shown in Fig. 7, from the scores of woods, Groups A, D and E scored higher, while Groups B and C generally scored lower, indicating that ash wood, oak wood and locust wood were superior to beech and cedar in the selection of hoe shanks and pegs. As for the scores of steels, Group 3 scored higher than Groups 1 and 2, indicating that spring steel was superior to Manganese 13 Steel and Type 45 Steel in the choice of cutterhead. Among the material combinations of hoe handle, embolus and cutterhead, D3 has the highest score, indicating that D3 has better production conditions in terms of depth and strength of the hoe tool. Therefore, by comparing the hoe tools made of the above materials, it is concluded that "Oak Wood + Spring Steel" is the optimal choice.

Conclusion

Based on the FEM, this study analyzed the performance of hoeing tools of different materials to provide theoretical references for future scholars in the selection of hoeing tools, research on agricultural tools and exploration of hoeing related culture. It is concluded that in the selection of hoe materials, ash, greenoka and acacia wood are preferred to beech and cedar wood for hoe handle and peg structure, and spring steel is preferred to Manganese 13 Steel and Type 45 Steel for cutterhead structure; and the combination of " Oak Wood + Spring Steel cutterhead" is selected to have the best mechanical properties.

It is worth noting that the model in this study was simplified, and therefore still has some limitations in the above results. In addition, a stress greater than the allowable stress of the corresponding material appeared during the finite element analysis, and the structure of the hoe can be further optimized and designed by ANSYS Workbench, which can make it possible to improve its structural strength with the same amount of material. This study only considered the case of wood at a particular moisture content, and can be followed up by continuing to study the performance of the hoe tool when choosing wood with different moisture contents. The cost of the hoe as a production tool also needs to be considered, and this can be further synthesized into a score by including the cost of production as a factor. In the study, only through the traditional hoe model on several hoe material selection performance comparison, subsequent research with reference to the ways and means of this study, to further explore the hoe handle and blade rigid connection (such as welding), different hoe work efficiency, but also can be further compared with wood, plastic, metal and other different hoe handle materials hoe mechanical differences, and thus enrich the hoe with the relevant theoretical research basis for the hoe selection. This will enrich the theoretical basis of hoeing and provide more comprehensive evaluation information for the selection of hoeing tools.

Declarations

Acknowledgements This study was financially supported by the Fujian Provincial Social Science Fund Base Major Project (FJ2023JDZ056), 2023 Fujian Provincial Education System Philosophy and Social Science Research Project (JAS23061), Scientific Research Foundation in Fujian University of Technology (Granted No. GY-Z220296) and Enterprise scientific research project of Huzhou Boloni Technology Co., Ltd (Granted No. 2021ZD01A).

Author contributions H. S. and K Z wrote the main manuscript text. K. S. and D. H. conducted the collection of wood properties prepared tables 1-2. C. L., F. Z. and Y. M. determined parameters and prepared figures 6-7 and tables 3.

Competing interests The authors declare no conflict of interest.

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Figures

Figure 1

Typical hoe model. a, Cutterhead model. **b**, Embolus model. **c**, Hoe handle model. **d**, Complete hoe model.

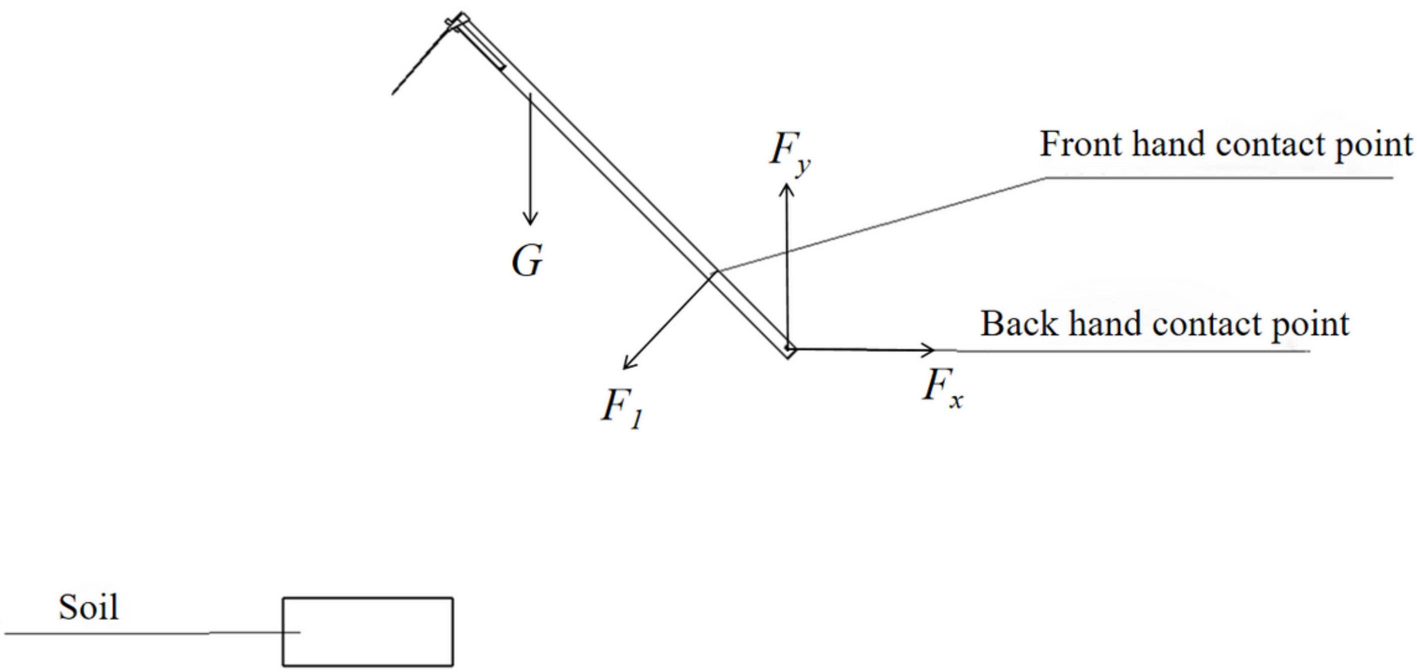

Figure 2

Pre-exposure analysis diagram

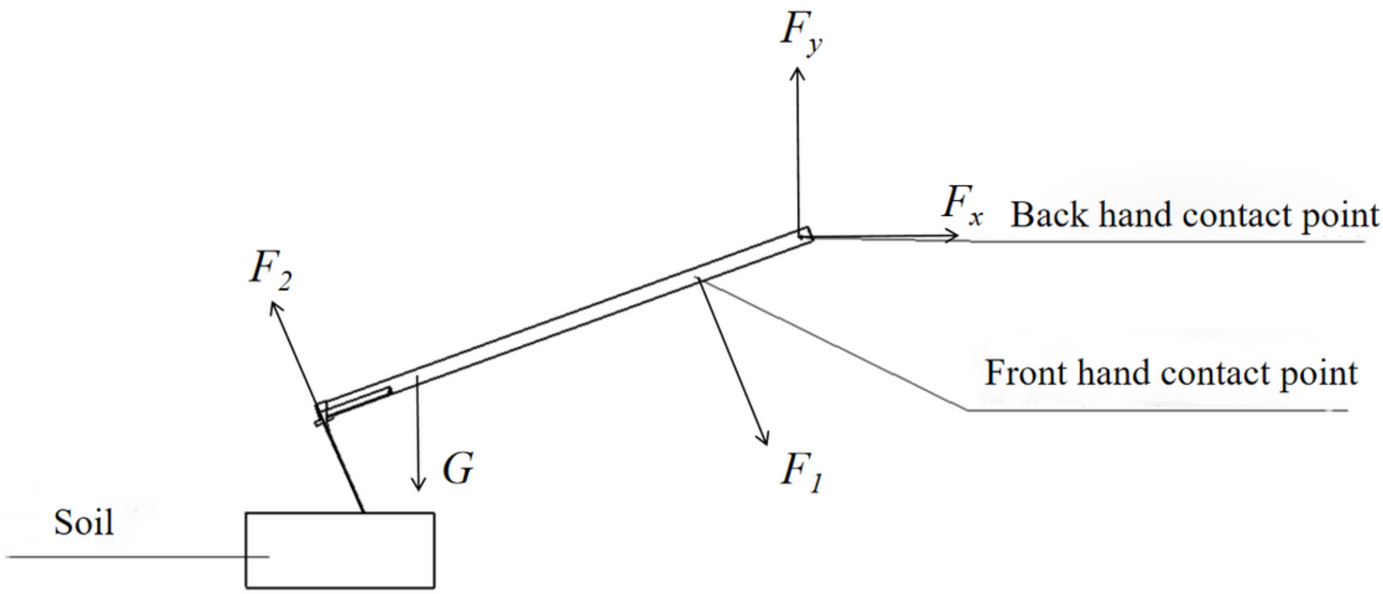

Figure 3

Analysis diagram at contact

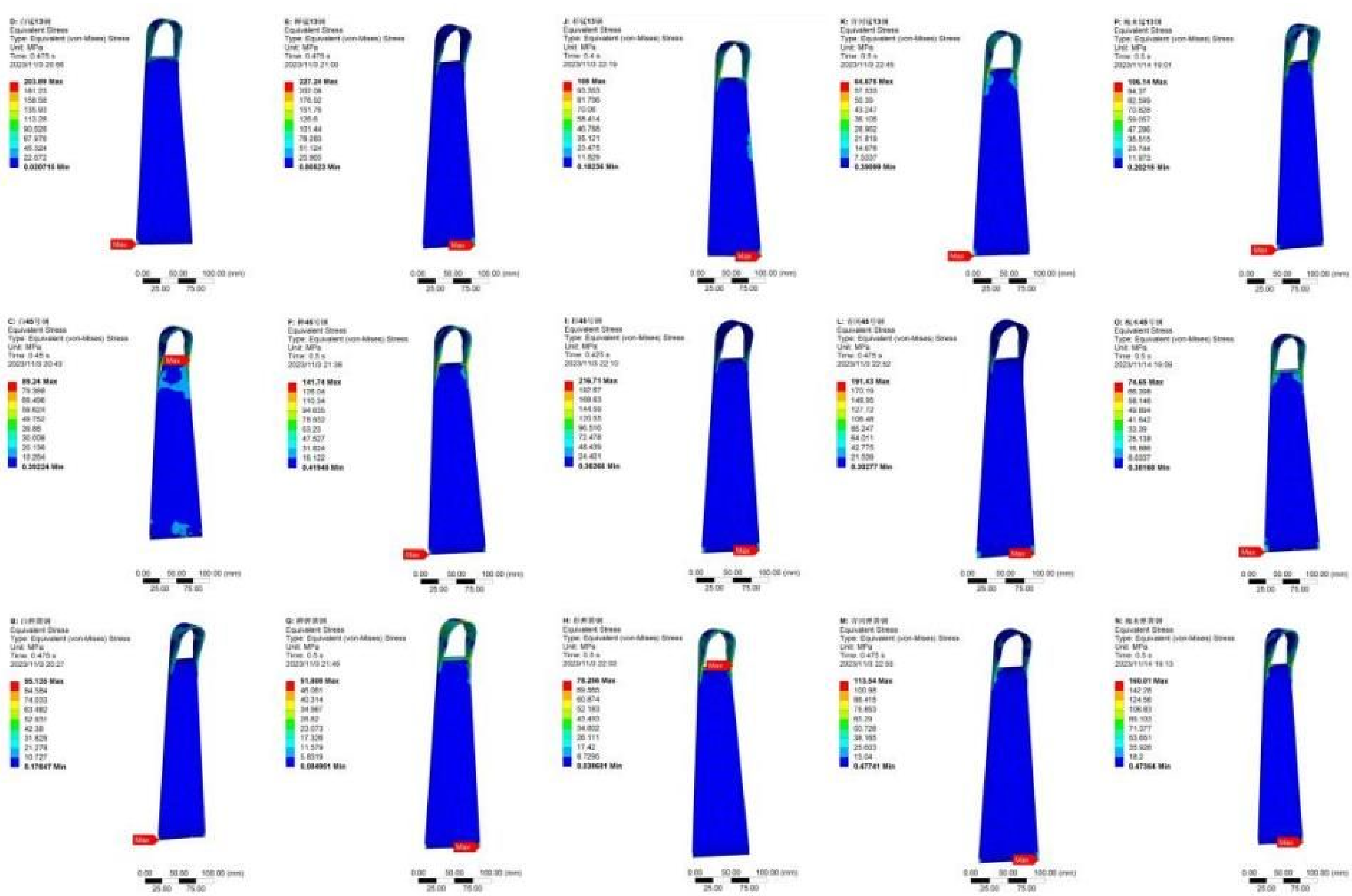

Figure 4

Stress nephogram at peak stress time of steel structure

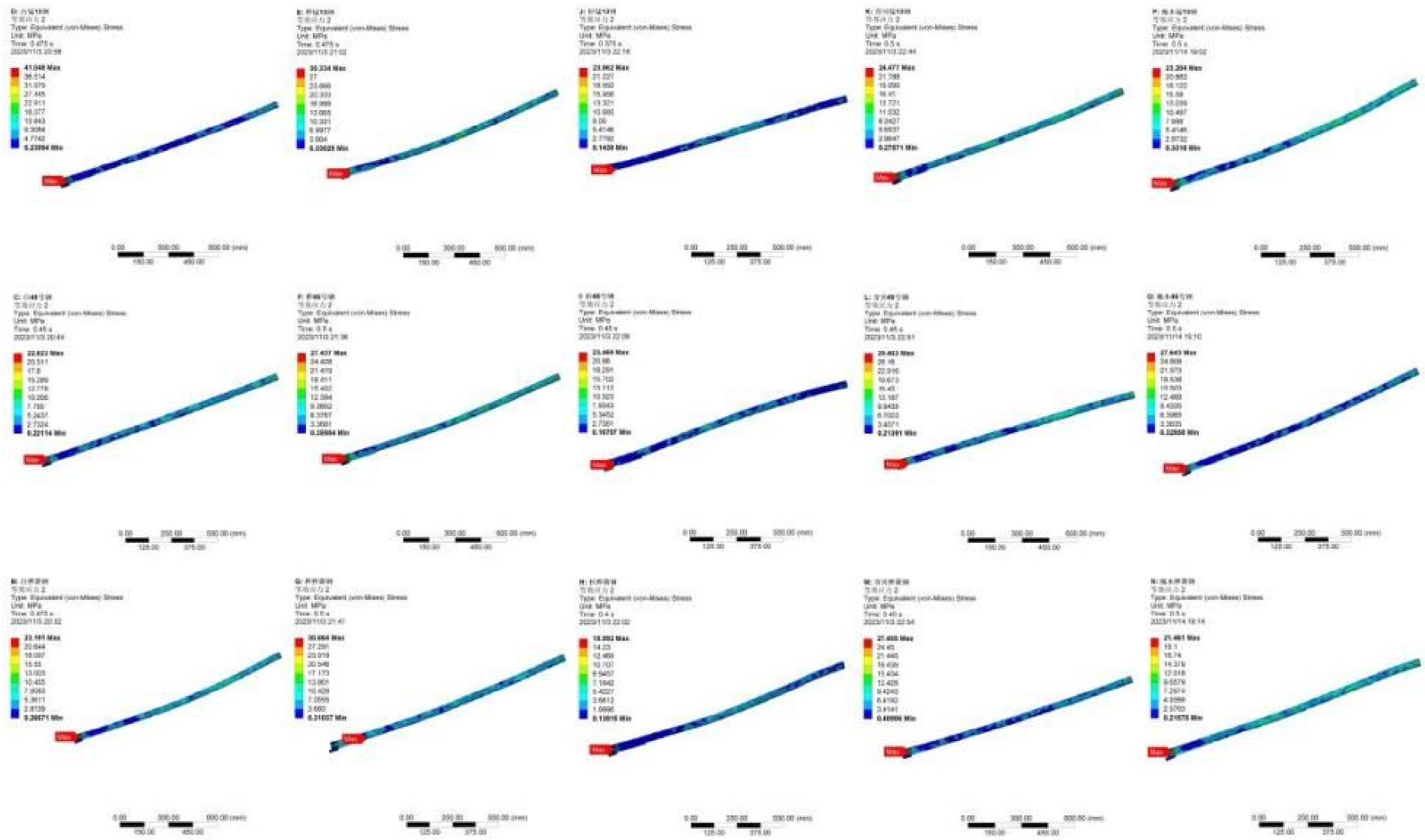

Figure 5

Stress nephogram of wood structure at peak stress time

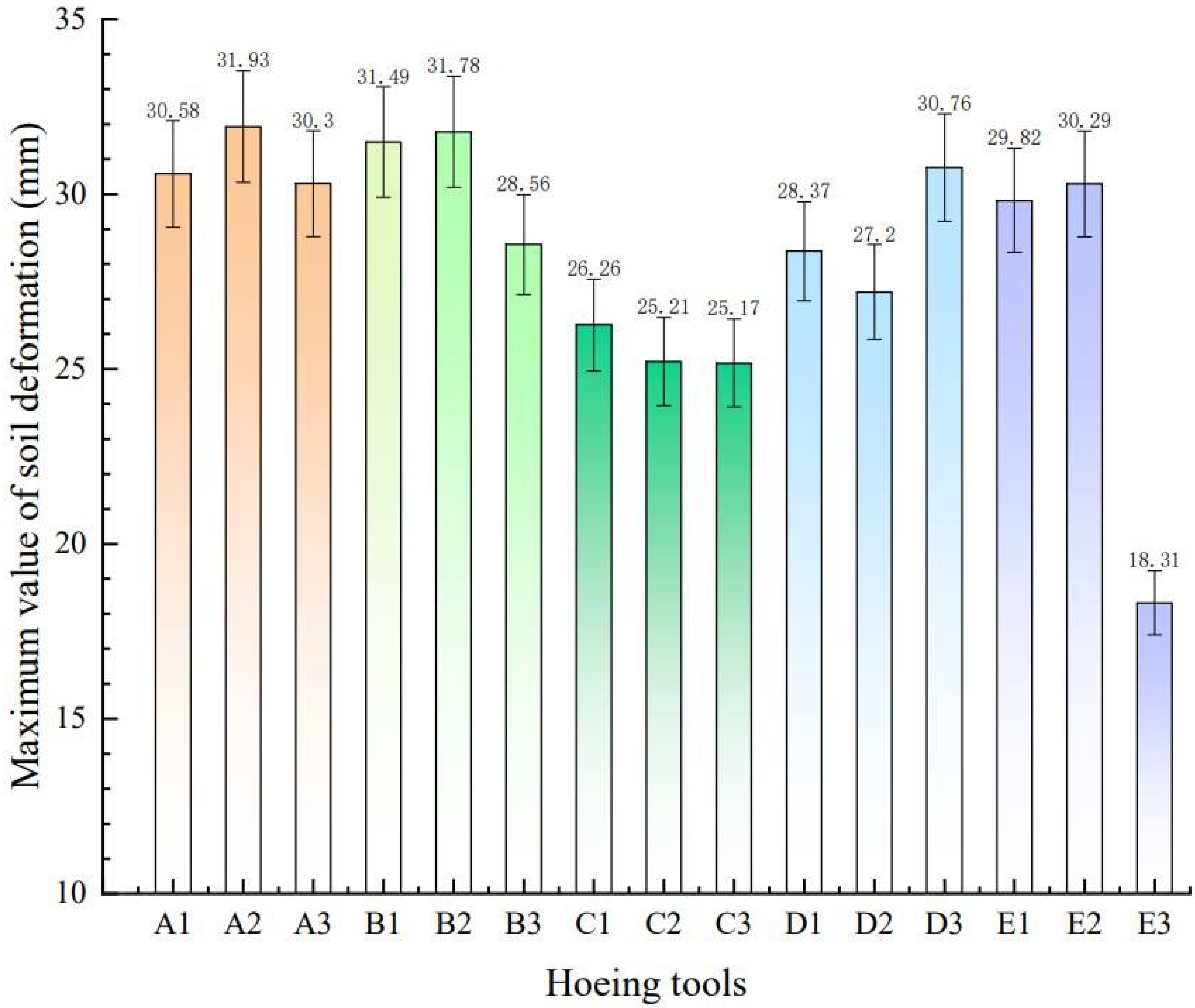

Figure 6

Maximum value of soil deformation

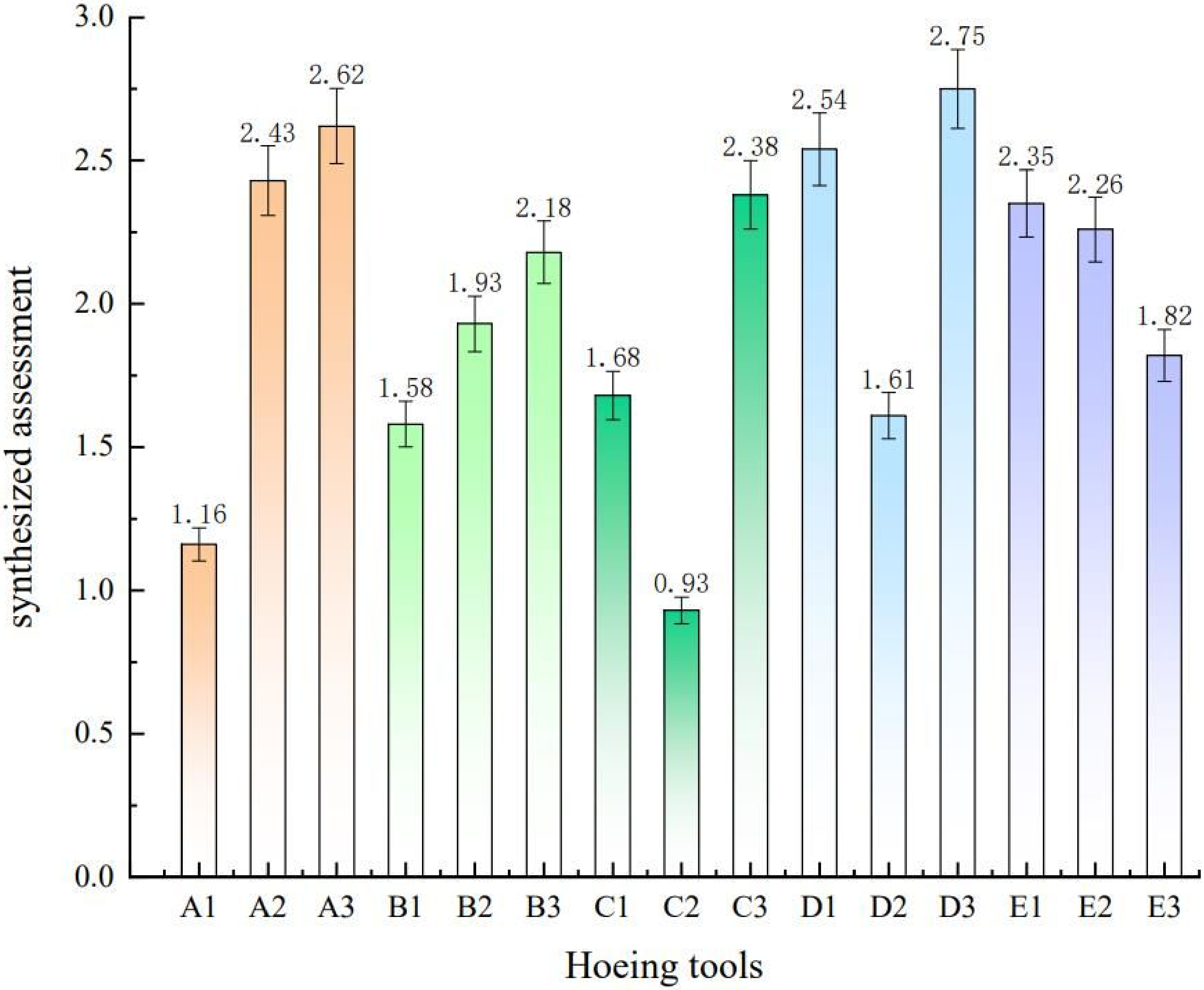

Figure 7

The overall score of each hoe