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Use of CAD system to determine the stability of machines and devices under static and quasi-static load

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Abstract:

For the conformity assessment process, the manufacturer is required to determine the stability of the machine/device, for issuing the declaration of conformity. The manufacturer should determine the stability of the machine/device already at the designing stage. Also, the users of older machines, must assess their safety in terms of stability and, if necessary, implement safety measures. The process of determining the stability of machines and devices under static and quasi-static load, using computer techniques is presented. A method of automating the calculation of stability assessment using a CAD software (Autodesk AutoCAD) and text editor (Microsoft Word) is discussed. The methodological assumptions of the problem are presented, and the developed solution is given. Automatically generated report (DOCX file), from stability assessment process of selected machine/device, containing both the input data and the results of the simulations and stability calculations are the final output of the developed tool. The database of the tool can be easily expanded by new classes of machines/devices. The computer tool was developed in English, which additionally increases its accessibility. Described method was used to calculate the longitudinal and transverse stability of the transportation platform transporting the longwall powered roof support. The example shows determination of limit angles of loss of stability, both for longitudinal and transverse inclinations. Developed software can be used by the following groups: students, manufacturers/designers of machines/devices and professionals involved in conformity assessment process.

Keywords: Stability, static load, computer simulation, transportation platform, section of longwall powered roof support, simulation results (report)

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1. Introduction

Stability of machines and devices

Stability is a key aspect of safety of using the machines that work in various industries, such as underground and opencast mining industry, agriculture, construction, as well as transport and storage. At the designing stage of a new machine, manufacturers use various methods for assessing the stability. These are analytical [1, 2, 3] and numerical methods [4, 5]. In the case of a high risk of loss of stability, based on the calculations results, further activities require using the strength calculations. These calculations with the use of FEM explicit method refer to the structures protecting the operators when the machine is overturned (the roll-over protective structures (ROPS) and tip-over protective structures (TOPS)) [6]. For conformity assessment process, the manufacturer is required to determine the stability of the machine/device, issuing the declaration of conformity. The manufacturer should determine stability of the machine and device at the designing stage. Also, the users of older machines, must assess their safety in terms of stability and, if necessary, implement the safety measures. To manufacture a machine or device and place it on the market in Europe, the manufacturer should meet the provisions of the Machinery Directive [7] or a corresponding harmonized standard. The Directive contains the following notes regarding the stability:

- Risk of loss of stability – machinery and its components and fittings must be stable enough to avoid overturning, falling or uncontrolled movements during transportation, assembly, dismantling and any other action involving the machinery. If the shape of the machinery itself or its intended installation does not offer sufficient stability, appropriate means of fixation must be incorporated and indicated in the instructions.
- Risk of slipping, tipping, or falling – parts of the machinery where persons are liable to move about or stand must be designed and constructed in such a way as to prevent persons slipping, tipping, or falling on or off these parts. Where appropriate, these parts must be fitted with handholds that are fixed relative to the user and that enable them to maintain their stability.
- Risks due to lack of stability – machinery must be designed and constructed in such a way that the stability required by Directive's section 1.3.1 is maintained both in service and out of service, including all stages of transportation, assembly, and dismantling, during foreseeable component failures and during the tests carried out in accordance with the instruction handbook. To that end, the manufacturer or his authorized representative must use the appropriate verification methods.

This article uses the following general definitions, the explanation of which should make it easier to understand the content presented below [8]:

- Machine vs device – the machine, unlike the device, has a drive motor as a source of energy for operation.
- Machine stability – the ability to maintain constant equilibrium, in the machine's operating conditions.
- Stability for static loads – stability considering only static loads (slowly changing over time).
- Stability for dynamic loads – stability with consideration rapidly changing both static and dynamic loads.
- Longitudinal stability – stability of the machine in the direction of its longitudinal axis, in accordance with the main direction of travel.

- Transverse stability – stability of the machine in the direction perpendicular to its longitudinal axis.
- Points of contact between the machine and the ground (tipping points or supports) – points through which the machine/device contacts the ground.
- Stability envelope – the outline of all the machine's/device's contact points with the ground.
- Tipping edges for longitudinal and transverse stability – lines passing through the outermost points of contact between the machine and the ground around which it can turn over, losing its stability.
- Force moment (torque) – the product of force and lever arm. The greater the force or the longer the lever arm, the greater the force moment (torque) acting on the component.
- Stability moment (Ms) – the sum of all moments that are intended to prevent the machine from tipping over.
- Overturning moment (Mo) – the sum of all moments that cause the machine to tip over. Everything that is not part of the overturning moment is part of the stability moment.
- Stability factor (X) – the ratio of the stability moment (Ms), counteracting overturning to the overturning moment (Mo), causing overturning, X = Ms / Mo, calculated relative to the same overturning edge (tipping edge).
- Limit angle of loss of stability – the angle of the transverse or longitudinal inclination of the ground, where the machine is still stable.
- Stability margin – extra payload that can be lifted before instability occurs.
- CG (Center of Gravity) – a point from which the weight of a body or system may be considered to act. In uniform gravity it is the same as the center of mass.

Existing methods of stability assessment

Criteria for machine stability are included in the Machinery Directive and in standards for specific types of machinery. The following criteria for stability can be distinguished [9]:

- Limit angles of loss of stability.
- Stability factor.

Limit angles of loss of stability

The limit angles of loss of stability can be calculated by setting the location of the center of gravity (CG) of the sum of the mass of the physical object and the weight of its payload. The main condition is that the CG lays within the contour of the machine's contact with the ground (stability envelope).

To calculate the limit angles, the criterion model of the physical object, located on a flat ground, with the specified center of gravity (CG), should be developed. Then straight lines should be lead through the CG and through the end contact points of the machine with the ground, defining the four tipping edges (E1 and E2 for longitudinal stability, E3 and E4 for transverse stability). The inclination angles of these straight lines to the Y axis will determine the limit angles of loss of stability (ANG1 and ANG2 for longitudinal stability, ANG3 and ANG4 for transverse stability). For these angles, the stability factor is equal to 1.0. A graphical method to calculate the limit angles of loss of stability is proposed below, Figure 1.

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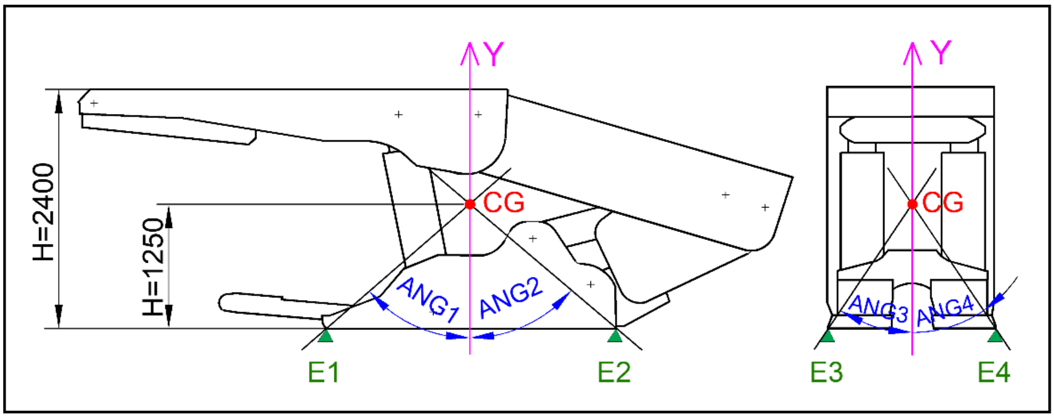

Fig. 1. Example of determining the limit angles of loss of stability for longwall powered roof supports [own source based on [9]]

Stability factor

It should be calculated for the criterion state of the machine/device, defined for the most unfavorable mass distribution and the most unfavorable external load condition, as well as the highest ground inclination allowed for the machine.

The criterion state of operation of the machine/device is a position of the machine/device together with its working equipment, for which various quantities are determined. In Figure 2 the example of determining the stability factor for the selected criterion state of the drilling and bolting car (machine), is presented.

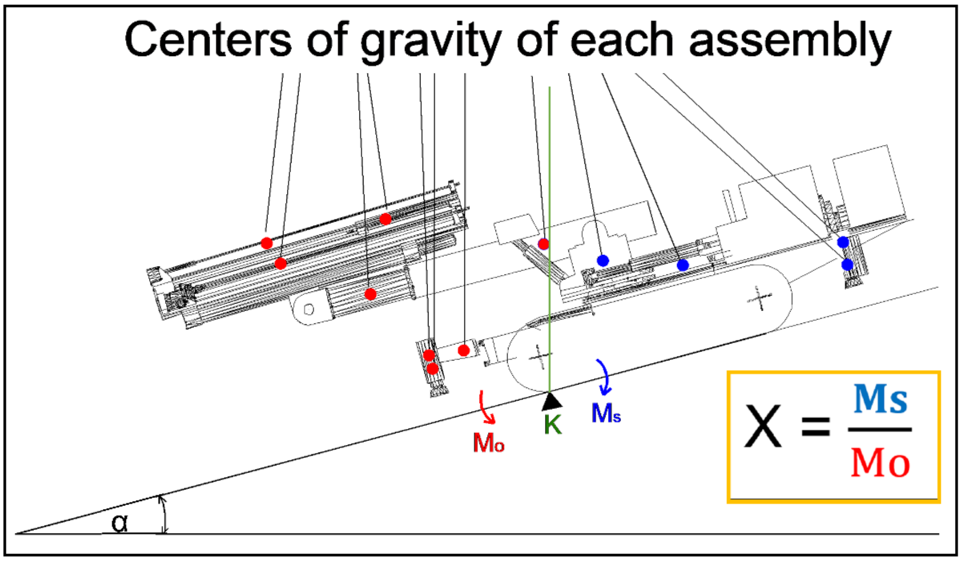

Fig. 2. Example of determining the stability factor for the selected criterion state of the drilling and bolting car (machine): X – stability factor, Ms – stability moment, Mo – overturning moment, K – tipping edge, α – angle of the ground inclination [own source based on [9]]

In the analyzed criterion condition, a machine is stable when the quotient of the sum of the setting moments (Ms) to the sum of the overturning moments (Mo), calculated for the same overturning edge (K), is greater than or equal to the value adopted by the standard. For mining machinery and equipment, the stability factor takes the values provided for in the individual standards:

- For longwall shearers [10] – the stability factor of the shearer with one-sided conveyor guidance should not be less than 1.25.

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– For roadheaders, continuous mining machines and impact machines [11, 12] – the stability factor should be not less than 1.25.
– For loaders [13] – the stability factor should be not less than 1.20.
– For drilling rigs [14] – the stability factor should be not less than 1.20.
– For mechanized casing [15] – when moving, in accordance with the manufacturer's instructions, free-standing casing sections should, over the entire height range, maintain stability with an inclination in each direction of up to 15° - a stability factor of 1.0.

2. Materials and Methods

Development of the method of stability assessment

The following assumptions have been made for an integrated software environment: the proposed method assumes development of a software tool to automate the process of determining and reporting the results from stability calculations for the selected machines/devices in the assumed criterion states of their operation. The developed tool should link the software from Autodesk (AutoCAD) and Microsoft (Word), thus enabling automation of stability calculations. The result is automatically generated as a report of the stability assessment process. The concept method is presented in Figure 3.

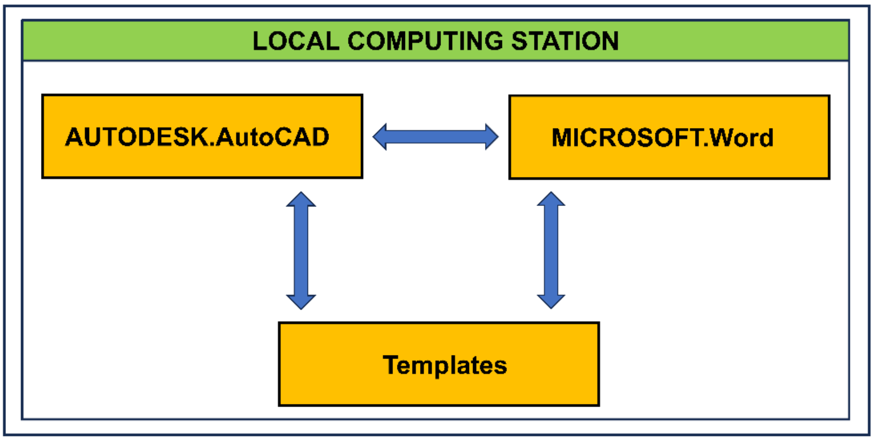

Fig. 3. Concept of the method for automating the assessment of stability [own source]

Any computer with the Microsoft Windows operating system, on which Autodesk AutoCAD and Microsoft Word software in the required versions are installed, can act as a local computing station. Users select the machine/device for stability assessment and copy an input data file template in Microsoft Word format. Then, they fill in the copied template with the required data (geometric data, mass data, loads). After completing this process, input data file becomes a calculation task. After creating the calculation task, users run the developed platform (Autodesk AutoCAD with program module) for simulation and calculations. After the calculations are completed, the input data file (calculation task) is filled with the calculations results, forming a single consistent stability calculation report file.

Stability calculations are made for all the assumed criterion states of machine/device operation. In Figure 4 the general algorithm for determining the machine/device stability under static load is presented.

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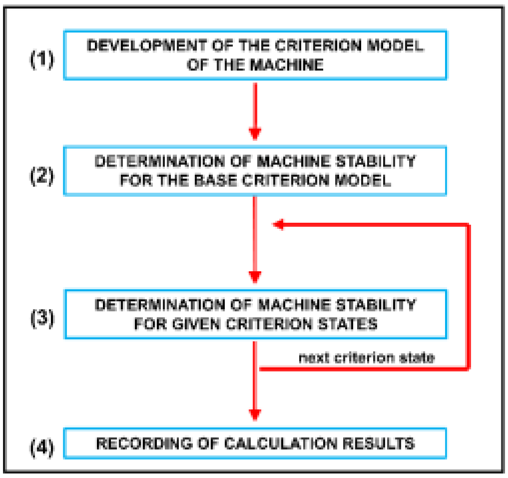


Fig. 4. General algorithm for determining the machine/device stability under static load [own source based on [9]]

The algorithm consists of the following four steps:

1. Development of the base criterion model of the machine – based on the input data, a criterion model of the machine is built.
2. Determination of machine stability for the base criterion model – stability of the machine for the base criterion model is determined, based on the following criteria: limit angles of loss of stability; stability factor. Stability of the assumed tipping edges and load cases of the machine.
3. Determination of the machine stability for a given criterion model – the criterion model of the machine is set for each criterion state. For each defined criterion state, stability of the machine is analyzed, as in step 2.
4. Recording the calculation results – once the calculations are completed, the results are collected and recorded in a form of the report.

For each criterion state of machine's/device's operation, it is possible to determine the following parameters:

– Limit angles of loss of stability (always).
– Stability factors (optionally – if the overturning moment can be determined).

Standards for machines/devices require that the stability factor calculations consider the load from not only the machine/device own weight, but also from any additional external loads that may appear during operation.

A machine/device is stable if the stability moment is greater than the overturning moment (stability factor is greater than 1). To assess the stability of a machine/device, all forces that stabilize and destabilize the machine/device must be considered.

Development of each module of the software tools (software platform)

During the development of the software tools, the following have been created:

– AutoLISP/VisualLISP functions – running inside AutoCAD: reading an input data file; building a computational model; carrying out simulation and calculations; creating a report [16, 17].

– VBA macros – running inside Word: reading an input data file; creating a report – filling a template [18, 19].

– ActiveX functions – providing communication between AutoCAD and Word.

– Templates of the selected machines/devices – input data for simulation and calculations; after filling with simulations and calculation's results they became a report.

Points of contact between the machine/device and the ground

Machines/devices contact the ground through the chassis, which transfers to the ground the weights of each assembly, the weights of the loads being transported, the weights of the operator(s), as well as the reactions resulting from external loads. The chassis are divided into four basic types, Figure 5:

– Caterpillar chassis (a) – found in mining roadheaders, drilling machines and loaders, excavators, machines for open pit mining, earthmoving machines.

– Tire wheeled chassis (b) – found in the machines for copper ore mining, excavators, earthmoving machines, drilling machines, forklifts.

– Rail wheeled chassis (c) – found in mining rail loaders, transportation platforms, overhead cranes, railroad cranes, public transport.

– Sliding chassis (d) – found in mining longwall shearers, coal ploughs.

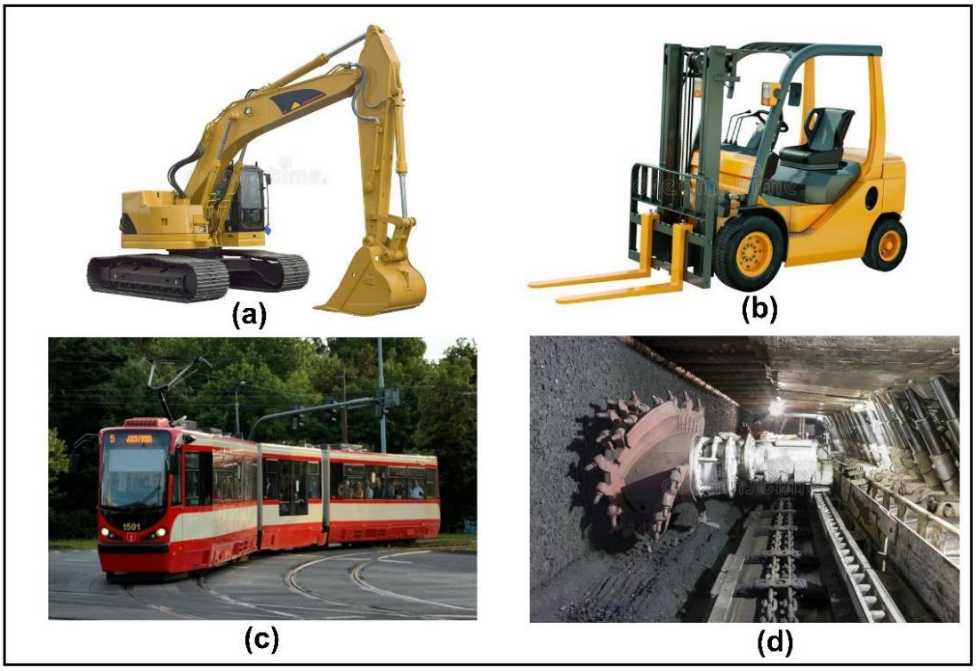


Fig. 5. Basic types of chassis [20, 21]: a) caterpillar; b) tire wheeled; c) rail wheeled; d) sliding

The points of contact between the machine and the ground are divided into:

– Primary (basis) – when the machine is moving.

– Additional – when the machine is working – they are designed to increase its stability.

Due to the possibility of movement in the plane of the ground, additional points of contact between the machine and the ground are divided into:

– Fixed – no possibility of movement in the plane of the ground: outriggers, shovel plate.

– Movable – can move in the plane of the ground: swing outrigger, loader bucket.

Figure 6 shows examples of contact points (fixed and movable) between the machine/device and the ground.

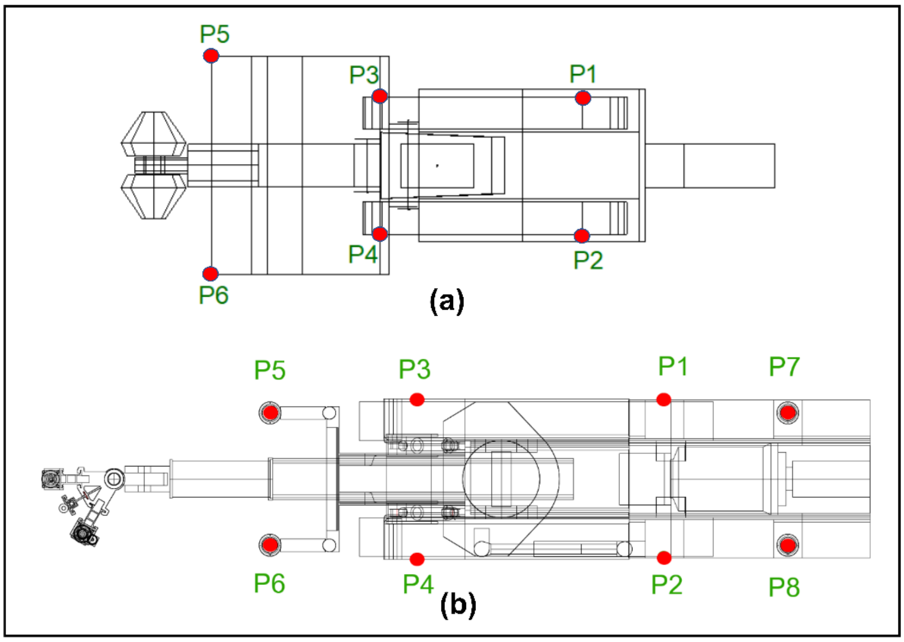


Fig. 6. Examples of points of contact of the machine/device with the ground: a) fixed (P1, P2, P3, P4, P7 and P8); b) fixed and movable (P5 and P6) [own source]

Tipping edges

Stability baselines are the lines drawn between points where the machine/device contact the ground (supports or tipping points). The points of contact between the machine and the ground define the tipping edges against which stability of the machine is determined. For the machines with no additional contact points, the tipping edges run through the points of contact between the machine's chassis and the ground.

For the machines with supports (additional contact points), stability should be calculated with the supports raised and with the supports retracted and placed, in their most favorable position, Figure 7.

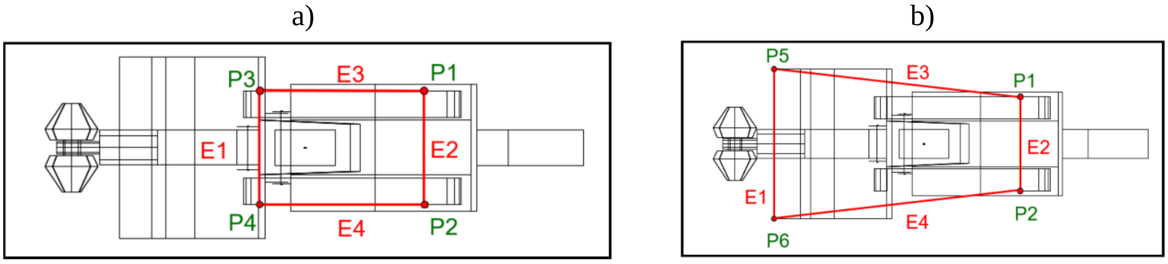


Fig. 7. Examples of tipping edges: E1, E2 – for longitudinal stability; E3, E4 – for transverse stability: a) raised shovel plate (loader); b) retracted shovel plate (loader) [own source]

Loads to the machine/device

The machine/device can be loaded by its own weight and by the forces, resulting from action of external loads. Loads from own weight include:

– Mass of each machine/device, assembly/subassembly/parts.
– Weight of the operator(s).
– Weight of the transported load.

This type of load always acts vertically (according to the gravity force). The mass data of the criterion model is determined using a 3D geometrical model of the machine/device made in CAD software.

Loads during the operation of machinery are divided into the following three groups: main, additional, and special. Main loads include all those loads that act continuously under the conditions of normal machine operation. Additional loads appear when the machine is in operation or when it is stopping. Special loads consist of those loads that should not occur during normal operation of the machine (e.g. machine's collision with the external object), but the possibility of their occurrence cannot be excluded [22].

The algorithm of stability calculations with external loads is as follows: each external force is decomposed into components: Fx, Fy, and Fz, in the coordinate system of the tipping edge for which the stability factor is determined [23]. Knowing each force parameters, the stability moment (Ms) or the overturning moment (Mo) are calculated, separately for each component relative to the given tipping edge.

Development of the report templates

The template enables preparation of a computational task – determination of the stability of the selected machine/device. Template file (DOCX) is divided into four main sections:

- Machine/device description.
- Input data.
- Computational model.
- Results of simulations and calculations.

Machine/device description

Describes the type and characteristic features of the machine/device.

Input data

Required to build a computational model. They include the following:

- Dimensions – the main dimensions of the machine/device and a transported load: range and default values.
- Mass distributions – mass distribution of the machine/device and a transported load, according to given Coordinate System: range and default values.
- External loads (if applicable) – forces and torques interacting with the machine/device. Only the case of static loads is considered (dynamic loads are neglected).

Computational model

Computational model of the machine/device, build on the input data entered. Apart from geometry and mass properties, it includes additionally:

- Points of contact between the machine/device and the ground.
- Tipping edges.

Results of simulations and calculations

Limit angles of loss of stability and coefficients of stability (if applicable), calculated for longitudinal and transverse stability. These values are calculated for each criterion state of the machine/device operation.

Selection of machines/devices

Eight classes of machines/devices have been chosen for the program's database of the developed tool, Figure 8 [20, 24]. Not all selected classes of machines/devices are placed in the database of the first version of the developed tool.

Fig. 8. Selected classes of machines/devices [20]

Implementation of the method

Described method was used to calculate the longitudinal and transverse stability of the transportation platform transporting the longwall powered roof support. The example below shows determination of limit angles of loss of stability, both for longitudinal and transverse directions.

Transportation task

It is necessary to determine the limit angles of loss of longitudinal and transverse stability, for the transport of longwall powered roof support, using rail transportation platform, Figure 9. Extreme dimensions of the longwall powered roof support are: 6000 mm (length – X axis) x 1670 mm (width – Y axis) x 1600 mm (thickness – Z axis). The roof support is attached to the transportation platform to form one rigid body (there is no possibility of displacement or rotation between them). A rail transportation platform (001-01 from the database of available machines/devices) should be used for transport. There are no external loads (forces and torques), interacting with the transportation platform. Only the case of static loads is considered.

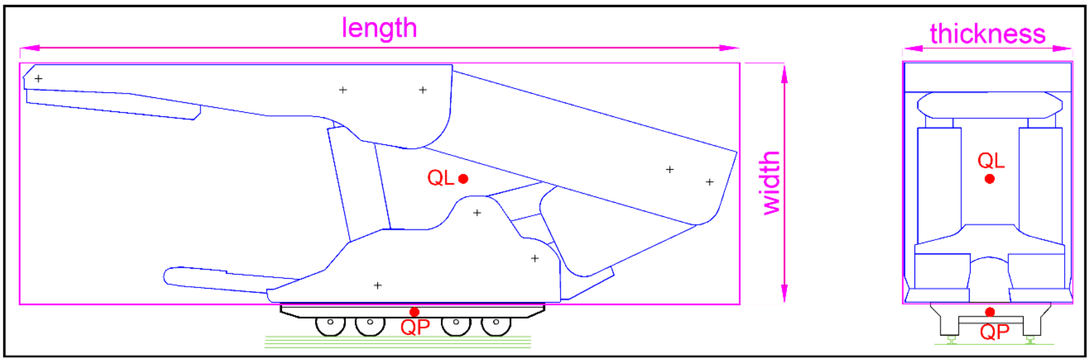
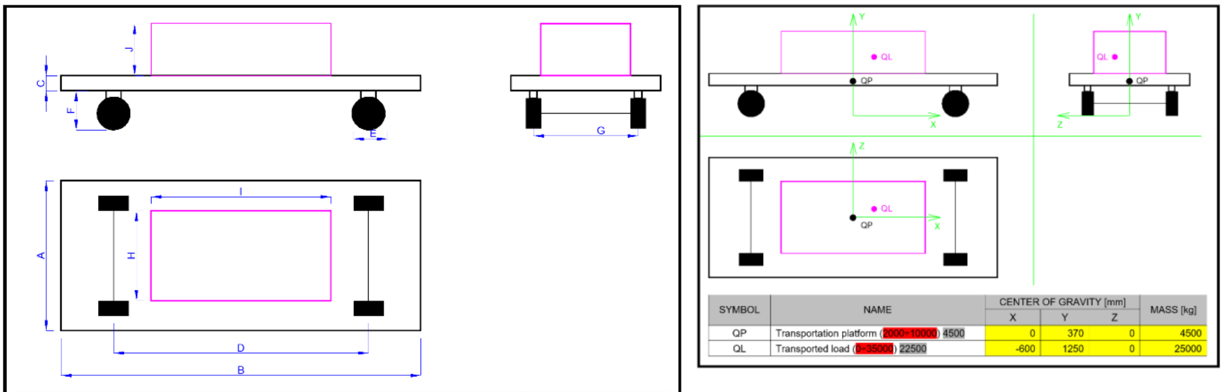


Fig. 9. Transport of the longwall powered roof support, using rail transportation platform. QP – center of gravity for transportation platform. QL – center of gravity for transported load [own source]

Input data

The main dimensions of the transportation platform and a transported load; mass distribution, according to given Coordinate System, are presented in Figure 10 (range and default values).

a) b)



SYMBOL	NAME	VALUE	UNITS
	TRANSPORTATION PLATFORM		
A	Width of the transportation platform (1500÷2000) 1750	1750	[mm]
B	Length of the transportation platform (3000÷6000) 4500	6000	[mm]
C	Thickness of the transportation platform plate (100÷300) 150	150	[mm]
D	Wheel base of the transportation platform (2000÷4000) 2500	2500	[mm]
E	Wheel diameter of the transportation platform (250÷500) 300 and E < F	300	[mm]
F	Height from the ground of the transportation platform (300÷600) 350	350	[mm]
G	Track width of the transportation platform (800÷1100) 900	900	[mm]
	TRANSPORTED LOAD		
H	Width of the transported load (100÷2000) 1500	1670	[mm]
I	Length of the transported load (100÷6000) 5000	6000	[mm]
J	Thickness of the transported load (100÷3000) 1250	1600	[mm]

SYMBOL	NAME	CENTER OF GRAVITY [mm]			MASS [kg]
		X	Y	Z	
QP	Transportation platform (2000÷10000) 4500	0	370	0	4500
QL	Transported load (0÷35000) 22500	-600	1250	0	25000

Fig. 10. Input data: a) dimensions; b) mass distribution [own source]

3. Results and Discussion

Based on the input data, a computational model was built for simulation and calculations. Figure 11 shows the results: limit angles of loss of stability for longitudinal stability and transverse stability.

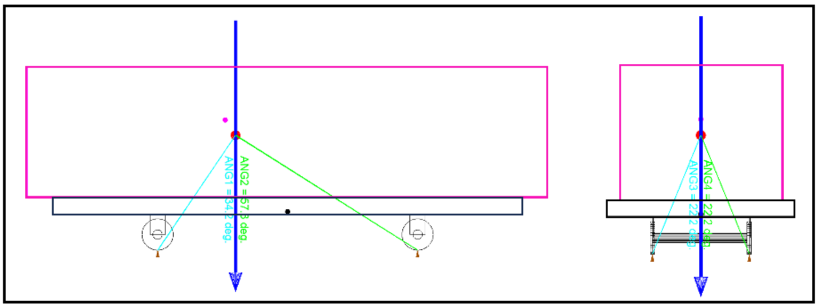


Fig. 11. Simulation and calculations results: limit angles of loss of stability: longitudinal stability (ANG1 and ANG2) and transverse stability (ANG3 and ANG4) [own source]

Difference in the angles for longitudinal stability (ANG1, ANG2) comes from the fact that the center of gravity (CG) of transported load (longwall powered roof support) is displaced relative to the X axis in the given coordinate system (-500 mm). Tilting the object (transportation platform and roof support) by a limit angle of loss the longitudinal stability (ANG1 or ANG2), causes the object to be unstable. Further increasing of the floor inclination causes exceeding the stability angle and the object loses its stability.

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4. Conclusions

The article presents a tool, developed at KOMAG Institute, that enables stability calculations for selected machines/device. The developed tool links together software from Autodesk (AutoCAD) and Microsoft (Word), which enables the automation of stability calculations under static and quasi-static loads. The result of the tool is a report file containing both input data and results from simulations and calculations. This file is created automatically. The database of the developed tool can be easily expanded by new classes of machines/devices. The advantages of the software tool include high speed of calculations, ease and intuitiveness of use and automatic generation of a report containing both input data and results. The developed tool can be used by the following groups:

- Students (for educational purposes – within the framework of classes on computer-aided design).
- Manufacturers/designers of machines/devices (determination of stability for the adopted criterion states, at the design stage).
- Professionals involved in conformity assessment (determination of stability for the adopted criterion states, at the stage of conformity assessment).

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