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Risk Management Regrading Crashing or Falling Down of Several Machine Tools in a Machine Shop at a Large Earthquake

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Abstract **-** In recent years, several large earthquakes have struck Japan and brought severe destruction and human loss. As a lesson for the future, large amounts of data obtained from the earthquake aftermath reports were studied in order to attenuate the effect of future catastrophes. In this regard, the current study attempted to develop a risk assessment criteria through existing seismic data and mathematical models for machine tools at the time of seismic activity. Particularly, data from the 1995 Great Hanshin earthquake, the 2004 Chūetsu earthquake and the 2011 Tōhoku earthquake was considered for this research. Moreover, the risk managements regrading crashing or falling down of several machine tools in the machine shop at the large earthquake model were considered and evaluated by using the three calculation models for the parallel displacement, the rotational movement and the overturn. It was concluded that; (1) the risk managements regrading crashing or falling down of several machine tools in the machine shop at the large earthquake model were cleared; (2) The use of anchor bolts to fully secure the machine tool to the machine shop floor was very effective in preventing the machine tool from crashing and falling down.

Keywords**:** Risk management, Earthquake, Machine shop, Machine tool, Crashing, Falling down

1. Introduction

The Great Hanshin-Awaji Earthquake of 17 January 1995 [1], the Great Chuetsu Earthquake of 23 October 2004 [2], and the Great East Japan Earthquake of 11 March 2011 [3] caused many victims and enormous damage. In response to these earthquakes, survey reports on the damage [4], activities for reconstruction and effective proposals for such activities [5] have been made, and disaster prevention measures for the future are continuously being taken based on the lessons of the past. On the other hand, after the earthquake, Japan's manufacturing industry stagnate due to the difficulty of revitalizing the local manufacturing industry, and the Japanese economy suffered a major blow [6], and the need to build an "earthquake-resistant manufacturing industry" has been strongly recognized [7] and [8].

Therefore, in this research, a machine tool management method is developed to prevent machine tool crashing and falling down accidents in a machine shop during earthquakes. Specifically, in Chapter 2, three earthquake data (acceleration) from the Great Hanshin-Awaji Earthquake, the Great Chuetsu Earthquake and the Great East Japan Earthquake are used to construct physical earthquake model for risk management. In Chapter 3, using the physical earthquake model from Chapter 2, risk management regarding crashing or falling down of machine tools in a machine shop during an earthquake is discussed and further discussed with regard to the layout, installation method and strength design of machine tools in the machine shop.

2. Large Earthquake Data and Geophysical Earthquake Model for Use in Risk Management

2.1. Data on Recent Large Earthquakes in Japan

An earthquake model has been developed for use in risk management, based on data from three large earthquakes that have occurred in Japan in recent years. The three large earthquakes covered are the Great Hanshin-Awaji Earthquake of January 17, 1995 [1], the Great Chuetsu Earthquake of October 23, 2004 [2], and the Great East Japan Earthquake of March 11, 2011 [3]. In general, the unit of earthquake acceleration is Gal (1 Gal = 0.01 m/s^2), however here mm/s^2 is used. The time, period and acceleration amplitude of each earthquake are very different, and even if the same structure is installed in three locations at the time, the stresses in the structure, the amount of movement, the amount of rotation and the presence of overturning are likely to be very different. Even if several of these structures were installed at the same location, their behavior would differ significantly depending on the direction and method of fixation. In addition, depending on the local ground conditions and the degree of the foundation on which the structure is installed, there is a possibility that earthquake conditions that exceed these acceleration curves may have occurred.

Table 1 shows the maximum values of the acceleration vectors in the north-south, east-west, vertical, horizontal directions (composite vectors of north-south and east-west), and in three-dimensional space (composite vectors of north-south, east-west and vertical) from the data of the Hanshin-Awaji, Chuetsu, and Tohoku earthquakes. Also shown in the table is the time at which that maximum acceleration vector occurred. This indicates that the Chuetsu earthquake was twice as violent as the other two earthquakes. This value is about 1.5 times higher than the acceleration of gravity. The time of the maximum acceleration is different in each direction, and this data suggests that the stresses in the structure, the amount of movement, the amount of rotation, and the presence or absence of falling down differ greatly depending on the direction in which the structure is installed.

Table 1: Maximum values regarding the vector of the acceleration for Hanshin & Awaji large earthquake disaster at 1995, Chuetsu large earthquake disaster at 2004 and Higashi-nippon large earthquake disaster at 2011. These data are also used for development of the physical earthquake model.

	North-South	East-West	Up-Down	On horizontal plane	On 3D space
Hanshin & Awaji large earthquake	5790 [18.0 s]	6170 [16.7 s]	3320 [16.4 s]	8460 Direction:43.2°	9090 Angle of declination:43.2° Direction: 21.5°
Chuetsu large earthquake	9240 [22.5 s]	16760 [16.9 s]	9550 [16.1 s]	19140 Direction:28.9°	21390 Angle of elevation: 28.9° Direction: 26.6.°
Higashi-nippon large earthquake	8560 [16.1 s]	7920 [19.1 s]	4810 [11.7 s]	11660 Direction:47.2°	12610 Angle of elevation: 47.2° Direction:22.5°

※Unit is mm/s², [ ] is the time from the start of earthquake to the time at maximum acceleration and Direction: North=90° , South= 270° , East =0° , West= 180°

2.2. The Earthquake Model Used in the Risk Management of This Research

Based on the data of large earthquakes in the previous section, an earthquake model is constructed for use in risk management. Figure 1 shows the shape of the acceleration-time curve for the earthquake model and its specification variables.

There are two curves, one for acceleration in one direction in the horizontal plane and one for acceleration in the vertical direction. The parallel behaviour of the structure on the horizontal plane is calculated by the maximum acceleration $\alpha_{NSEW\text{-}MAX}$ in one direction on the horizontal plane, and the maximum translational distance *DH* is calculated, and the maximum structure behaviour is assumed to have a possibility of parallel behaviour on the circumference with the radius *DH*. The amplitude of the earthquake is assumed to be unidirectional (assuming that the structure cannot reverse for some reason), and the maximum possible translational motion in one direction is assumed in later calculations. Similarly, the rotational behaviour of the structure on the horizontal plane was assumed to act in such a way that the acceleration in one direction on the horizontal plane produced the largest moment, and the rotation angle A_{Hn} was calculated at each support point. The falling down behaviour of the structure was calculated by phasing the vertical acceleration so that it reached an upward maximum when the acceleration in one direction on the horizontal plane reached a maximum value, and by phasing the vertical acceleration so that it reached a timing when it was most likely to overturn. Table 2 shows the geophysical earthquake model used in the risk management of this research. For the

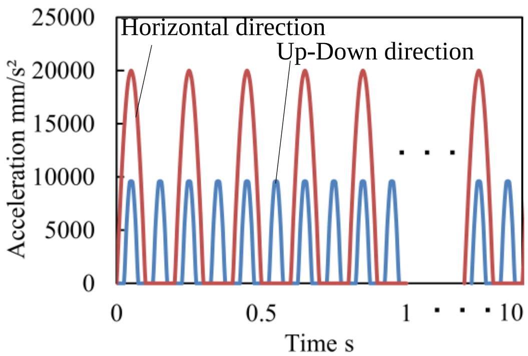


Fig. 1: Schematic view for the physical earthquake model for risk management regarding a machine tool. This model is used for risk management regarding a machine tool during a large earthquake.

Table 2; Physical earthquake data for the model in Fig. 1. This data is used for risk management regarding a machine tool during a large earthquake.

Direction	Parameters	Symbol	Physical earthquake data
Horizontal	Max. acceleration	α_{NEWS}	20000 mm/s²
	Term	Tr_H	10 s
	Cycle	C_H	0.2 s
	Number	N_H	50
Up-down	Max. acceleration	α_{UD}	10000 mm/s²
	Term	Tr_{UD}	10 s
	Cycle	C_{UD}	0.1 s
	Number	N_{UD}	100
Earthquake cure: One side wave and Triangular type			

specification variables of the earthquake model shown in Fig. 1 above, the individual specification variables are extracted from the three earthquakes data of the Great Hanshin-Awaji Earthquake, the Great Chuetsu Earthquake and the Great East Japan Earthquake in Section 2.1., and the maximum values are selected and combined. In this research, the earthquake model shown in Fig. 1 and Table 2 was used for the subsequent discussion and investigation.

3. Risk Management of Machine Tool Crashing and Falling Down in a Machine Shop During A Large Earthquake

3.1. Risk Management for Machine Tool Crashing Prevention

As a risk management measure to prevent machine tool collisions, a machine tool arrangement and machine tool distance that provides sufficient space to prevent machine tools from colliding with each other in parallel or rotational behaviour during an earthquake are considered. The geometry of the machine tool structure used is shown in Fig. 2 and its specifications are given in Table 3. For this machine tool structure (Fig. 2, Table 3), the parallel and rotational behaviours in the physical earthquake model (Fig. 1, Table 2) in Chapter 2 are calculated by the physical calculation models in the previous research [9]. The results of this calculation are only an example of how the machine tool structure shown in Fig. 2 behaves in the horizontal plane in response to the excitations shown in Table 2, however it is easy to vary the values of the representative variables in Tables 2 and 3 to prevent collisions between machine tool structures of different specifications and with different magnitudes of earthquake assumed. In addition to the model shown in Fig. 2 (Centre of gravity G_{Basic}, Height of the centre of gravity $H_{g\text{-basic}}$), the model with the workpiece, table and saddle moved to the uppermost position and the workpiece and table moved to the left (-y direction) (Centre of gravity $G_{Working}$, Height of the centre of gravity $H_{g\text{-Working}}$) was used to calculate the maximum value.

Figure 3 shows the results of the calculation for the moving area of the machine tool structure during the physical earthquake model. Figure 3(a) shows that a machine tool structure with a floor area of V m × S m is subjected to translational motion in a region of radius 2.2 m by the earthquake. The 360°arrangement of the machine tool structure is taken into account. As shown in Fig. 3(b), since the machine tool structure rotates around the support point, the outermost distance 1900 mm is calculated from the centre of gravity $G_{working}$ of the machine tool structure after the rotational motion in order not to collide with the adjacent machine tool or the wall, and furthermore, assuming that the machine can be installed freely in 360°. A square of 3800 mm (= 1900 mm x 2) per side is assumed to be the moving area due to rotation in an earthquake. All the

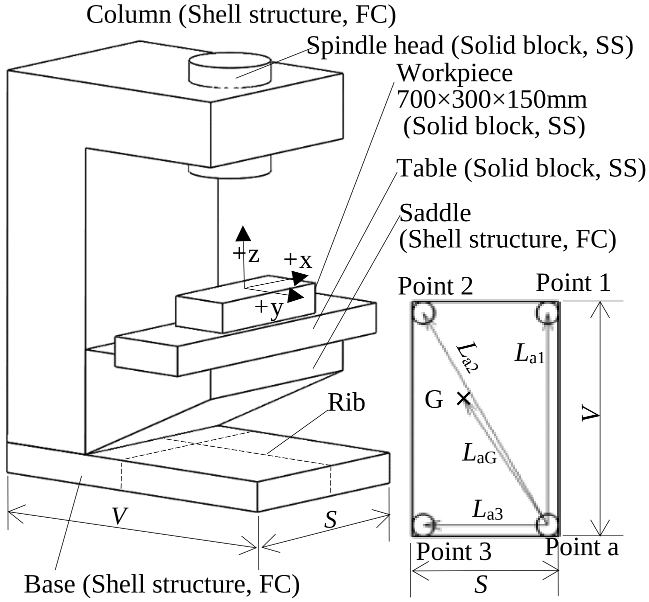


Fig. 2: Schematic view of the machine tool structure for consideration of the behaviour during the physical earthquake model（SS: steel, FC: cast iron）.

Table 3: Machine tool structure data in Fig. 2. This data is also used for consideration of the behaviours during the physical earthquake.

Specification	Parameter	Symbol	Data
Area on the floor	Vertical dimension	V	1600 mm
	Horizontal dimension	S	1000 mm
Height of the center of gravity	High	$H_{g\text{-basic}}$ $H_{g\text{-working}}$	1020 mm 1200 mm
Distance between the support point a and the X	X = G	$L_{a\ G\text{-basic}}$ $L_{a\ G\text{-working}}$	950 mm 990 mm
	X = Pint 1	L_{a1}	1450 mm
	X = Pint 2	L_{a2}	1680 mm
	X = Pint 3	L_{a3}	850 mm
Mass	Machine tool	$M_{machine\ tool}$	3480 kg
	Workpiece	$M_{workpiece}$	250 kg
	Total	M_{total}	3730 kg
Moment of inertia		Ia	3670 kgm^2

・Structure : Solid block or Shell structure (thickness=25 mm)
・Material : Steel (specific gravity 7.8) or Cast iron (s. g. 7.2)
・Specification of the physical earthquake ⇒ Table 2
・Physical calculation models: [9]
・Coefficient of friction between structure and floor: 0.3

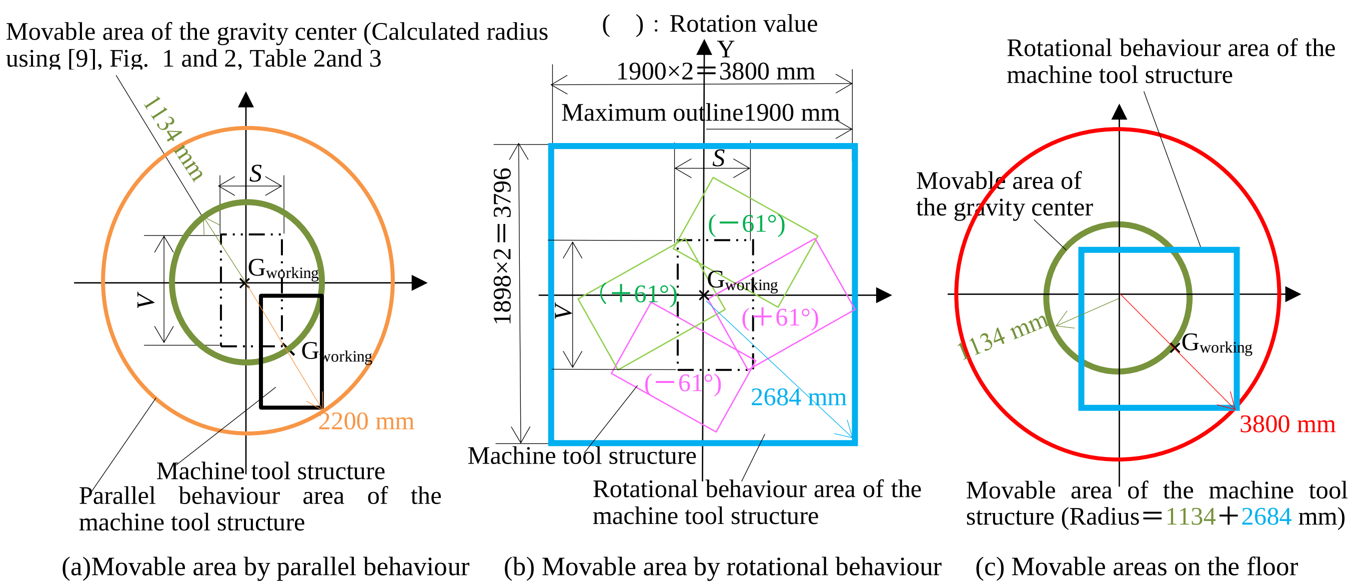
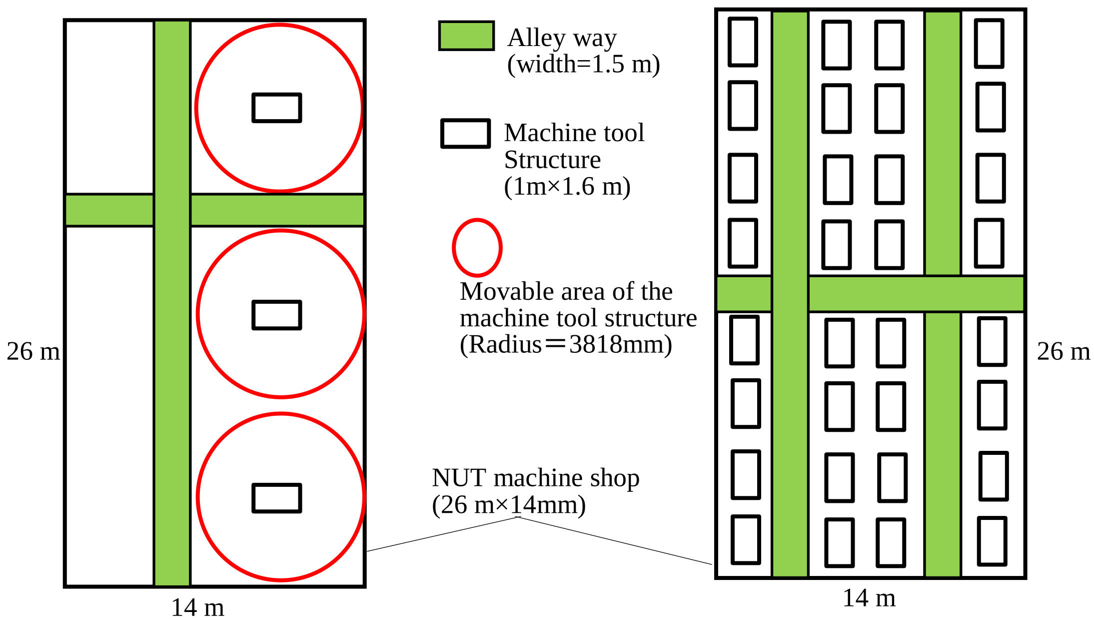


Fig. 3: Movable areas regarding the machine tool structure (Table 3) during the physical earthquake (Table 2). These movable areas were calculated for countermeasure of the crashing between several machine tools by the physical calculation models in the previous research [9]. This method was used for risk management of the machine tools during a large earthquake.

rotations were considered at the same time, when the support point with the largest amount of rotation moved in four places. Finally, as shown in Fig. 3(c), superimposing the moving area of parallel behavior (Fig. 3(a)) and rotational behavior (Fig. 3(b)), the moving area of this machine tool structure in an earthquake was the area within a radius of 3.8 m.



(a) Safe machine tool placement without the cramping

(b) Safe machine tool placement with the cramping using several anchor bolts

Fig. 4: Safe machine tool placements without or with the cramping using several anchor bolts during a large earthquake in NUT (Nagaoka University of technology) machine shop. When the cramping of the machine tool was used, the machine tool number increased, of course safe machine tool placement was also ensured.

Figure 4 shows the machine tool layout and machine tool distance to prevent machine tools from colliding with each other in translational or rotational motion during an earthquake. In the machine tool centre of Nagaoka University of Technology (floor area 26 m × 14 m), several machine tools as shown in Fig. 2 are designed to be installed as many as possible under the condition that machines do not collide with each other or with the wall of the factory during an earthquake. Aisles 1.5 m wide in length and width are mandatory. Fig. 4(a) shows the case of Fig. 3 considering the moving area within a radius of 3.8 m due to an earthquake, and Fig. 4(b) shows the case where all the machine tool structures are fixed with anchor bolts. By fixing all the machine tool structures, the number of machine tools in the factory was improved from 3 to 32. The design of anchor bolts to prevent collisions of machine tool structures is discussed in the next section on risk management for falling down prevention.

3.2. Risk Management to Prevent Machine Tools from Falling Down

Safety measures to prevent machine tools from falling down during an earthquake are discussed. The possibility of the machine tool falling down during an earthquake can be calculated using the physical calculation model in the previous research [9] for the falling down behaviour during the physical earthquake model (Figure 1, Table 2) in Chapter 2, using the machine tool structure (Figure 2, Table 3) described above. By simply changing the values of the representative variables in Tables 2 and 3, it is easy to take measures to prevent the tipping over of machine tool structures of different sizes and specifications. It was confirmed that the machine tool structure shown in Fig. 2 tipped over in the earthquake shown in Table 2, whether the centre of gravity during machining was low ($H_{g\text{-Basic}}$ = 1020 mm) or high ($H_{g\text{-working}}$ = 1200 mm). This is because the vertical earthquake acceleration in Table 2 (modified from the Chuetsu earthquake [2]) is higher than the gravity acceleration. It was also confirmed that the system tipped over at the time of the Great Hanshin-Awaji Earthquake and the Great East Japan Earthquake [3]. Thus, machine tool structures are extremely prone to falling down when the timing of vertical and horizontal earthquake accelerations coincide. For example, for the earthquake model in Chapter 3 used in this research, when the earthquake acceleration in the vertical direction of the Great East Japan Earthquake is 5000 mm/s^2 [3], the condition for the machine tool structure in Fig. 2 to topple over is when the height of the centre of gravity $H_{g\text{-working}} > 0.16$ m. It is common for machine tools to move heavy workpieces to a higher position for machining or to move a heavy spindle head up and down. Thus, the height of the centre of gravity of the machine tool may change during actual machining. Therefore, as a risk management measure to prevent the machine tool from falling down, it is essential to check that the machine tool will not tip over even at the height of the machine tool centre of gravity when the maximum workpiece weight in the machine tool specifications is raised to the maximum height, using a physical calculation model in the previous research [9] and a physical earthquake model (Table 2). The safety factor can then be ensured by changing the data of the physical earthquake model to the less dangerous one. Furthermore, anchoring machine tools to the factory floor with anchor bolts can be effective. In this research, anchor bolts are discussed in terms of collision prevention and falling down prevention. Table 4 shows the forces acting on anchor bolts for fixing machine tools during an earthquake. The forces acting on a single anchor bolt are classified into the maximum force F_{maxH} in the horizontal plane, which occurs when the parallel and rotational behaviours are suppressed to prevent collision, and the maximum force F_{maxV} in the vertical direction, which occurs when the falling down behaviour is suppressed to prevent tipping. It is assumed that the machine tool structure is permanently fixed to the floor by anchor bolts, and the mass times acceleration force is used here instead of the dynamic force calculated from the momentum-force product relationship.

Table 4: Strength calculation condition for the machine tool fixing using several anchor bolts during a large earthquake (the used anchor bolt was made by steel and its allowable stress was 120 MPa).

Counter-measure	Behaviour	Physical calculation model	Impacted acceleration in an earthquake	Considered strength and its force.
Clashing	Parallel	the previous research [9]	Max. acceleration α_{NEWS}: 20 m/s^2	Shear strength 26.4 MPa and its force 18650 N
	Rotational			
Falling down	Falling down		Max. acceleration α_{NEWS} and α_{UD}: 20 m/s^2 and 10 m/s^2	Pulling strength 100.8 MPa and its forces 71200 N

The maximum force F_{maxH} acting on a single anchor bolt to prevent collision can be calculated using Eq. (1) below.

$$F_{\mathrm{maxH}} = M \times \alpha_{\mathrm{NEWS}} \div N = 3730\ \mathrm{kg} \times 20\ \mathrm{m/s^2} \div 4\ \mathrm{bolts} = 18650 \quad (\mathrm{N}) \tag{1}$$

Here, M is the mass of the machine tool structure, α_{NEWS} is the maximum seismic acceleration on the horizontal plane (see Table 2), and N is the number of anchor bolts used in one machine tool structure. After calculating the maximum seismic force F_{maxH} acting on one anchor bolt, the diameter D_{H} of the bolt which can tolerate the maximum seismic force F_{maxH} can be calculated by Eq. (2) based on the value of the maximum seismic force F_{maxH} and the allowable stress σ_a (120 MPa) of the bolt in Table 4.

$$D_{\mathrm{H}} = \left(\frac{4\times F_{\mathrm{maxH}}}{\pi\times\sigma_a}\right)^{\frac{1}{2}} = \left(\frac{4\times 18650}{\pi\times 120\times 10^6}\right)^{\frac{1}{2}} \fallingdotseq 0.015\ (\mathrm{m}) = 15\ (\mathrm{mm}) \tag{2}$$

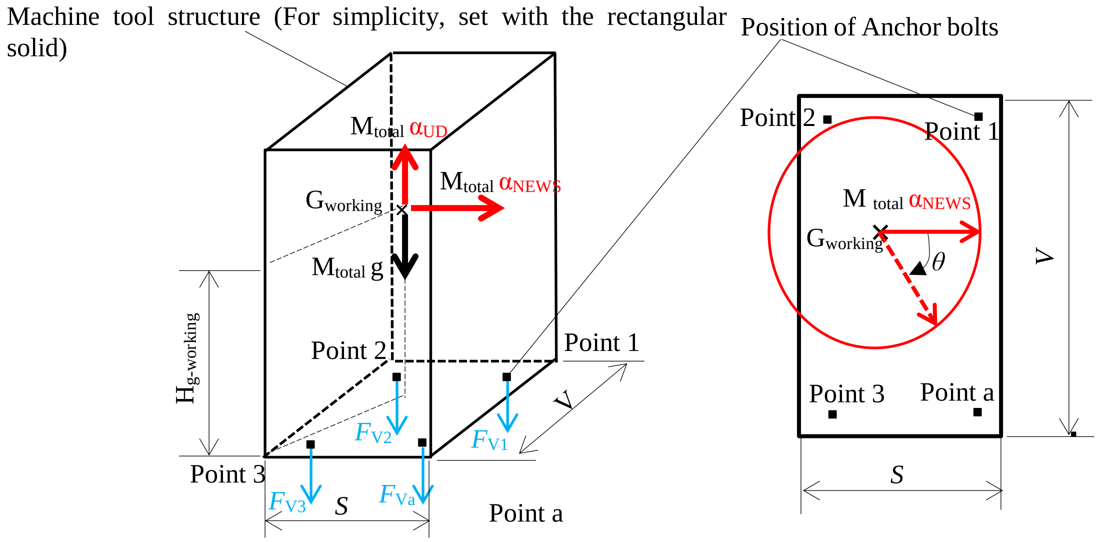


Fig. 5: Diagram of the forces on the machine tool structure with fixing for countermeasure of the falling down.

Next, the maximum excitation force F_{maxV} in the longitudinal direction acting on a single anchor bolt for fixing to prevent overturning is considered. As shown in Fig. 5, when four support points of the machine tool structure (Fig. 2, Table 3) are fixed with anchor bolts to the physical earthquake model (Fig. 2, Table 3), the load F_V applied to each anchor bolt to prevent falling down has different values. Depending on the direction and magnitude of the maximum earthquake acceleration α_{NEWS} in the horizontal plane and the direction and magnitude of the maximum earthquake acceleration α_{UD} in the vertical direction, the excitation force F_V on each anchor bolt will also vary.

As shown in Fig. 5, the maximum load F_{maxV} of one anchor bolt is calculated as follows: (1) First of all, one arbitrary anchor bolt is assumed to be the centre of falling down, (2) The centre of gravity of the machine tool structure ($H_{g\text{-}working}$) is the centre, and the radius of the maximum earthquake acceleration α_{NEWS} is defined as its direction in θ coordinates, (3) The direction of the maximum earthquake acceleration α_{UD} in the vertical direction is always upward so that the anchor bolt is loaded, (4) Calculate the reaction force of the remaining anchor bolts by solving the force diagram in Fig. 5, (5) Calculate the largest load $F_{betterV}$ when the anchor bolt is the centre of falling down by changing the variable θ by 360° using the successive substitution method, (6) The remaining anchor bolts are set as the centre of overturning, and the same procedure (2) to (5) is applied to calculate the largest load $F_{betterV'}$, (7) Determine the maximum excitation force F_{maxV} from the largest load when each anchor bolt is the centre of falling down. As shown in Fig.5, under the conditions of the physical earthquake model (Fig.1, Table 2), the machine tool structure (Fig. 2, Table 3), and the fixation of four support points, the maximum excitation force F_{maxV} was 71200 N (acting at Point 2 when Point a is the centre of overturning (θ= 57° in the direction of α_{NEWS}), calculated from the procedure of (1) to (7). After calculating the maximum clamping force F_{maxV} acting on one anchor bolt for fixation, the diameter D_V of the bolt which can allow the maximum clamping force F_{maxV} can be calculated by Eq. (3) based on the value of F_{maxV} and the allowable stress σ_a (120 MPa) of the bolt in Table 4.

$$D_V = \left(\frac{4\times F_{maxV}}{\pi\times\sigma_a}\right)^{\frac{1}{2}} = \left(\frac{4\times71200}{\pi\times120\times10^6}\right)^{\frac{1}{2}} \fallingdotseq 0.028\ (\mathrm{m}) = 28\ (\mathrm{mm}) \tag{3}$$

Finally, the magnitude of the combined force FmaxHV (FmaxH+FmaxV) of the maximum excitation force FmaxH (horizontal) and the maximum fastening force FmaxV (vertical) acting on a single anchor bolt is determined in order to take into account both crash and falling down preventions. The magnitude of the combined force FmaxHV is 73610 N (=

(FmaxH2+FmaxV2)0.5 = (18650²+71200²)0.5). Based on this value and the allowable stresses of the bolts of 120 MPa in Table 4, the diameter DHV of the bolt that can tolerate the combined force FmaxHV can be calculated using Eq. (4).

$$D_{HV} = \left(\frac{4\times F_{maxHV}}{\pi\times\sigma_a}\right)^{\frac{1}{2}}\times\cos\phi = \left(\frac{4\times 73610}{\pi\times 120\times 10^6}\right)^{\frac{1}{2}}\times\cos 14.7°\fallingdotseq 0.028\ (m) = 28\ (mm) \quad (4)$$

Here, ϕ represents the inclination of the surface on which the combined force F_{maxHV} acts. Since the combined force F_{maxHV} is inclined by ϕ° (= 14.7°) from the maximum clamping force F_{maxV}, the plane of action is inclined by ϕ° accordingly.

From the above Eqs., the size of the anchor bolts to prevent crash and falling down was determined to be M30. All anchor bolt sizes are unified to this size. This makes it possible to arrange the machine tools in a way that takes into account both safety and productivity, as shown in Fig. 4(b). At the same time, it is necessary to secure the strength of the floor surface to hold the anchor bolts.

4. Conclusion

The results of this research are summarized as follows; (1) Three physical computational models in the previous research [9] were used to calculate the parallel, rotational and falling down behavior of a machine tool during an earthquake. (2) Based on the data of three earthquakes, the Great Hanshin-Awaji Earthquake, the Great Chuetsu Earthquake and the Great East Japan Earthquake, a physical earthquake model was developed, and a risk management method for the crash and the falling down of machine tools in the machine shop during a large earthquake was proposed. (3) The necessity of risk management of machine tools is proposed based on the actual data of the Chuetsu earthquake, and the effectiveness of anchoring machine tools with anchor bolts is clarified as a risk management method for preventing machine tools from crash and falling down.

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