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Impact Effect on the Behavior of Land and Underwater Pipes

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ABSTRACT

Pipelines are under the effects of destructive sudden loads including accidental drops, ship anchors, rock falls, trawlers fishing and military attacks in addition to environmental loads. In this study, finite elements method (FEM) supported numerical and semi-analytical analyses of the same pipe section have been carried out according to the sudden loads caused by falling objects both underwater and on land. Abaqus finite elements analysis software is used in the numeric analysis. While the pipe-falling object interaction is modelled in the analysis of the pipeline on land, the pipe-falling object-water interaction is modelled in the underwater pipeline. Bidirectional fluid-structure interaction (FSI) analysis is utilized in the water-pipe-falling object interaction modelling. A fully nonlinear free surface simulation is performed by Coupled Eulerian Lagrangian (CEL) technique in the FSI analysis. Impact parameters such as accelerations, displacements impact forces and energy absorption, are determined for both land and underwater pipe sections. Semi-analytical solutions of the pipe models have been generated by using the resulting impact forces. Thus, numerical analyses have been verified with the semi-analytical models. In addition, the effect of water on impact behaviour as well as the free surface movement of water during impact effect has also been determined.

1. Introduction.

The pipeline consisting of pipes, fittings, pumps, booster stations, intake and outtake parts etc., is a significant system in civil engineering field. The pipelines are used for various purposes in the sea and on the land.

They usually take on tasks for the transportation of various fluids and gases across different locations. The pipelines are able to convey water, sewage, oil and natural gas. So, they are indispensable for the industry and the agriculture. Although the pipelines provide several benefits for the infrastrucure, they may struggle against environmental difficulties such as earthquakes, landslides, storms, soil liquefaction and sudden impact effects. Explosions, vehicle collisions and rock falls are some incidents of impact effects on the land and submarine pipelines (Ahmad Fuad et al. 2019, Lin et al. 2024, Rao et al. 2022).

Sudden falling objects changes mechanical properties of structural members due to dynamic effects. Stress values change because of these effects at the moment of impact. Damage expands beyond the impact point during such impact incidents. Therefore, severe damage and losses may be occurred. Several experimental (Erdem, Berberoğlu and Gücüyen, 2023: Mehrjardi et al. 2024) and numerical studies (Gücüyen and Erdem 2024: Yılmaz et al. 2024: Odina, Hardjanto and Walker, 2018) have recently been developed by many scientists to facilitate better understanding of these complex impact related events. In addition to these, semi-analytical studies including single (SDOF) and multi degree of freedom (MDOF) methods have been widely used to model dynamic response of structures under sudden loads.

In the study of (Hou and Li, 2023) mass-plate model is simplified as SDOF structure and shock damage boundary of it is determined under the acceleration-time history of a shock-waveform. Real model is created by finite element method

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(FEM) to verify the results of SDOF. Therefore FEM model undergoes shock load cases with different frequency bands. (Hadianfard and Shekari, 2019) have investigated nonlinear dynamic response of the multi-story steel frame one-way flexural members under impact load. Two different blast loads are affected to structure. The frame is reduced to numerically identical SDOF structure. Comparisions of the responses at different supporting conditions are made with codes. Similarly (Al-Thairy, 2016) have simplified steel column model to SDOF structure under blast load . Idealized pressure–time function of blast load is used in the SDOF analysis Analysis is performed by resistance function and the results are verified by numerical analysis. (Fallah and Louca, 2007) have adopted resistance function in the SDOF model of steel blast wall. Resistance function is obtained from FEM. Displacement time histories of the SDOF model is collate with FEM results. As different from the pipelines on land, investigation of marine pipelines under falling impact loads is performed by considering fluid-structure interaction (FSI) analysis and can be generated by Coupled Eulerian Lagrangian (CEL) technique. Abaqus finite element software is commonly employed in the interaction modelling (ABAQUS User's Manual, 2015). In the literature survey, it is seen that the CEL technique has been used in a few studies in modeling the behavior of underwater pipes under the effect of sudden falling objects (Jiang and Zhao, 2024).

As the studies in the literature are reviewed, it is seen that there is a lack of practice about the sudden impact effect on the pipes that are surrounded by water. Therefore, this study tends to investigate the underwater and land pipes under impact loading due to falling objects via bidirectional fluid structure interaction. For this purpose, the CEL procedure of Abaqus software is used for numerical simulations. Different land and underwater pipe models are considered for the solutions. Structural outputs such as accelerations, displacements, impact forces, external pressures, as well as velocity and stress distributions are obtained for each numerical model. Afterwards complex pipe models simplified as SDOF models by means of impact forces extracted from FE analysis. The numerical models are validated by SDOF models in the end.

2. Numerical Models.

While three dimensional underwater numerical models are presented by Figure 1.a, SDOF idealization of above ground pipe models are shown in the Figure 1.b. The pipes are created as stationary water filled and empty. Four different cases are investigated to determine the internal and external environment effects on the pipes in the end.

Time dependent impact force values that are achieved from numerical analyses are shown in Figure 1.c. Diameter (D) and thickness (t) of the pipe models are 0.6 m, 5.0 m and 0.018 m respectively. The length of the pipe models and other dimensions of the external environment of the underwater pipe models are specified by the rates exhibited in Figure 1.a. Drop height of the falling object is taken as 5 m. In addition, mass of the striker is utilized as 250 kg in the numerical simulations. The steel material having Young's modulus of 210 GPa, Yield Stress of 210 MPa and t density of 7850 kg/m^3 is utilized in pipes. In addition, water is modelled as EOS material with the velocity of sound (c_0) in water 1450 m/s, the density (ρ) of 998 kg/m^3 and the dynamic viscosity (μ) of 0.0010 Ns/m^2. C3D8R element types are utilized for the pipe sections. However, C3D10M element types are used for the falling object sections. Besides, EC3D8R element types are applied to the water region for the Eularian part. The distance between nodes is taken to be 0.018 m as same as the pipe thickness in the contact regions. The value is considered as 0.025 m for the rest of the geometry. While 12323776 nodes and 12159120 elements are utilized in the Eularian part of the outside of the pipe, 268956 nodes and 255840 elements are utilized inside of the pipe. 72812 number of nodes and 38628 number of elements are used in the Lagrangian part. Impact loading is applied as a result of free falling motion. Because of this reason, no other load is effected to the system except gravity. Fixed supports are defined at both ends of the pipes.

3. CEL Analysis.

Abaqus exploits the combination of Eulerian-Lagrangian approach that is named as CEL method utilizing the following equations in the numerical analysis. Mass, momentum and conversation of energy equations in turn are defined by Eqs. (1-3).

$$\frac{D\rho}{Dt} + \rho\nabla \cdot v = 0 \tag{1}$$

$$\rho\frac{Dv}{Dt} = \nabla \cdot \sigma + \rho b \tag{2}$$

$$\frac{De}{Dt} = \sigma : D \tag{3}$$

In these equations, material velocity, density, the Cauchy stress, body force, and internal energy per unit volume are represented by v, ρ, σ, b, and e respectively.

$$\frac{D\varphi}{Dt} = \frac{\partial\varphi}{\partial t} + v \cdot (\nabla\varphi) \tag{4}$$

Conservation equations that are embraced in the Lagrangian procedure are obtained in the general form of Eularian approach via Eq. (4). However, φ symbolizes the randomly selected solution factor.

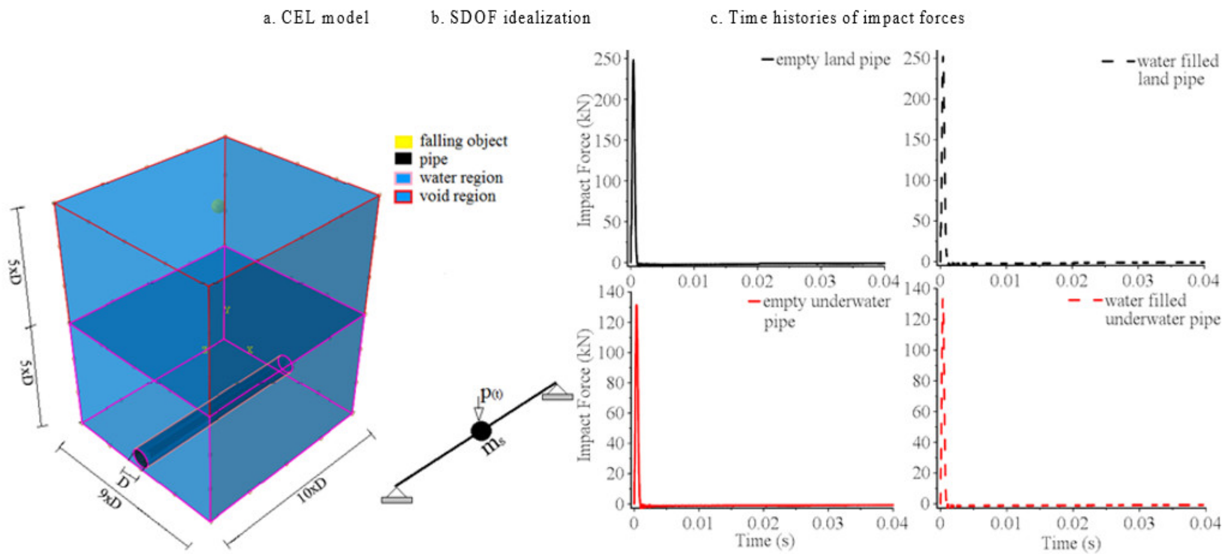
$$\frac{\partial\varphi}{\partial t} + \nabla \cdot \Phi = S \tag{5}$$

Φ symbolizes the flux function and S represents the source term in Eq. (5). This equation could also be given as two independent equations as below.

$$\frac{\partial\varphi}{\partial t} = S \tag{6}$$

$$\frac{\partial\varphi}{\partial t} + \nabla \cdot \Phi = 0 \tag{7}$$

Figure 1: CEL and simplified models with impact forces.



Source: Authors.

As the spatial time derivative is changed by the material time derivative on the fixed mesh, Eq. (6) becomes same with the standard Lagrangian formulation. Afterwards, the deformed mesh switches to the original fixed mesh, and the volume of material transported between adjacent elements is required to be calculated in the solution of Eq. (7). Mass, energy, momentum and stress parameters for the Lagrangian method are implied for the flow of the material between adjacent elements through the transport algorithms.

3.1. CEL application to mentioned model.

As the problem becomes significant at the moment of contact, the value of time increments are defined as 0.070 sec before the beginning of impact effect. However, the value is taken as 1x10^{-8} sec when the contact has started between the striker and the pipe. After carrying out the numerical analysis, impact forces are transformed into equation of motion of SDOF model. Time dependent impact force values for empty land, water filled land, empty underwater and water filled underwater pipes are shown in Figure 1.c. Maximum impact force values are obtained from Figure 3 as 248.39 kN for empty land pipe, 252.41 kN for water filled land pipe, 131.58 kN for empty underwater pipe and 133.27 kN for water filled underwater pipe.

4. Semi-analytical Analyses.

In this part of the study, semi-analytical analysis are carried out for all models by means of generalized SDOF method as rendered in Figure 1.b. This method is applied to models by derivation of the Eq. (8). Time histories of impact forces are given by Figure 1.c. are embedded for external forces (F*) on the right side of the equation.

$$m^* \frac{\partial^2 Y_{(t)}}{\partial t^2} + c^* \frac{\partial Y_{(t)}}{\partial t} + k^* Y_{(t)} = F*_{(t)} \tag{8}$$

Where m* c* and k* are generalized mass, damping and stiffness respectively. Mathematical definitions of these terms are given by the following equations m_s is structural mass, E is the modulus of elasticity, I is the moment of inertia, a is the damping coefficent, L is the lenght of pipe. In addtion to those ψ (z) is the shape function of the pipe, which should satisfy loading and boundary conditions.

$$m^* = \int_0^L m_s \psi_{(z)}{}^2 dz \tag{9}$$

$$c^* = aEI \int_0^L \left(\frac{\partial^2 \psi_{(z)}}{\partial z^2} \right)^2 dz \tag{10}$$

$$k^* = EI \int_0^L \left(\frac{\partial^2 \psi_{(z)}}{\partial z^2} \right)^2 dz \tag{11}$$

Sequentially given values of m*, c* and k* are 0.79 (kNs^2/m), 800 kNs/m and 66361 kN/m for Land 1, 1.539 (kNs^2/m), 2000 kNs/m and 66361 kN/m for Land 2, 0.79 (kNs^2/m), 2800 kNs/m and 66361 kN/m for underwater 1 and 1.539 (kNs^2/m), 4000 kNs/m and 66361 kN/m for underwater 2. While empty pipe models are indicated by 1 index, water filled pipe models are indicated by 2 index. In this paper, the Runge–Kutta method is performed to solve Eq. (8) under dynamic initial boundary conditions given below.

$$t = 0 \Rightarrow Y_{(0)} = 0,\ Y_{(L)} = 0,\ \dot{Y}_{(0)} = 0,\ \dot{Y}_{(L)} = 0 \tag{12}$$

The Runge–Kutta method as given below interprets the basic relationships at the beginning, middle and end of the time steps (?t) (Barltrop and Adams, 1991). Semi-analytic analyses are continued for the same step time and iteval with numerical analyses.

$$\ddot{Y}_{(t)} = m^{-1}\left(F_{(t)} - kY_{(t)}\right)$$
$$\dot{Y}_{t+\Delta t} = \dot{Y}_t + \ddot{Y}_t \Delta t \qquad (13)$$
$$Y_{t+\Delta t} = Y_t + \dot{Y}_t \Delta t$$

5. Results.

Firstly, acceleration and displacement values are obtained from 100 mm distance from the impact point from FEM analyses. Afterwards, displacements are also computed SDOF analyses. Differentiate operations is performed on displacement values of SDOF analyses to verified FEM results. Maximum acceleration and displacement values are given in Tables 1 and 2. While empty pipe models are indicated by 1 index, water filled pipe models are indicated by 2 index in the results section.

Table 1: Numerical results for land pipe models.

Results \ Analyses	Land 1 FEM	Land 1 SDOF	Land 1 SDOF/FEM	Land 2 FEM	Land 2 SDOF	Land 2 SDOF/FEM
Displacement (mm)	4.17	4.62	1.10	4.24	4.75	1.12
Acceleration (g)	7608	8346	1.09	7657	8402	1.09

Source: Authors.

Table 2: Numerical results for underwater pipe models.

Results \ Analyses	Underwater 1 FEM	Underwater 1 SDOF	Underwater 1 SDOF/FEM	Underwater 2 FEM	Underwater 2 SDOF	Underwater 2 SDOF/FEM
Displacement (mm)	0.32	0.36	1.12	0.35	0.42	1.20
Acceleration (g)	3261	3651	1.11	3308	3493	1.05

Source: Authors.

While the average value of SDOF/FEM for displacement is calculated as 1.13 and 1.085 for acceleration, the standard deviation value of SDOF/FEM for displacement is calculated as 0.044 and 0.025 for acceleration according to Tables 1, 2. These results reveal that a significant model a strong relationship is constituted between analyses. Time histories of acceleration, displacement and impact force versus displacement values are presented in Figures 2-4. starting with the first drop movement.

After completing the numerical analyses, Von-Mises stress distributions that are shown in Figure 3 are determined from the software. The values are obtained after the full contact is completed between the falling object and the pipe. Elemental pressure values at the impact point on the pipes changing by time are given in Figure 4.

Interaction of falling object, pipe and water is seen in the Figure 5 from the moment the falling object touches the water until it strikes the pipe.

Conclusions.

In this study, an incremental non-linear dynamic analysis for a 6 m long span of the pipeline is performed by Abaqus software. Impact loading is applied for the constant values of drop

Figure 2

Figure 2. a. Time histories of acceleration values

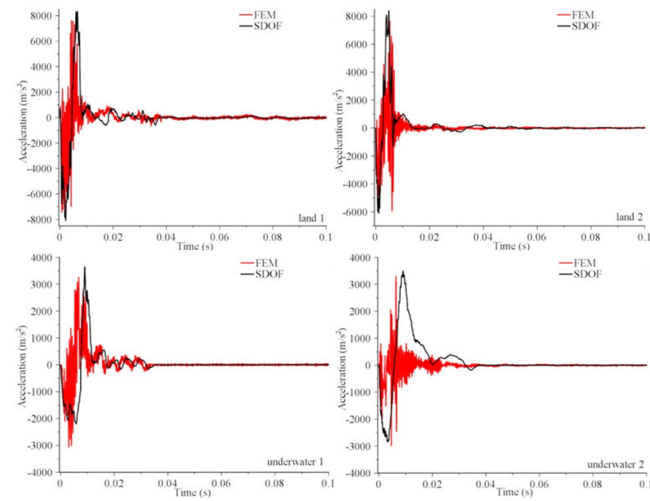


Figure 2. b. Time histories of displacement values

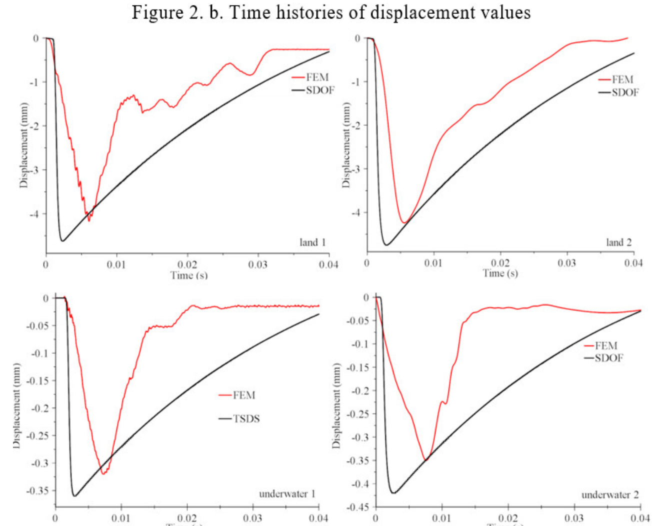


Figure 2. c. Impact force versus displacement values

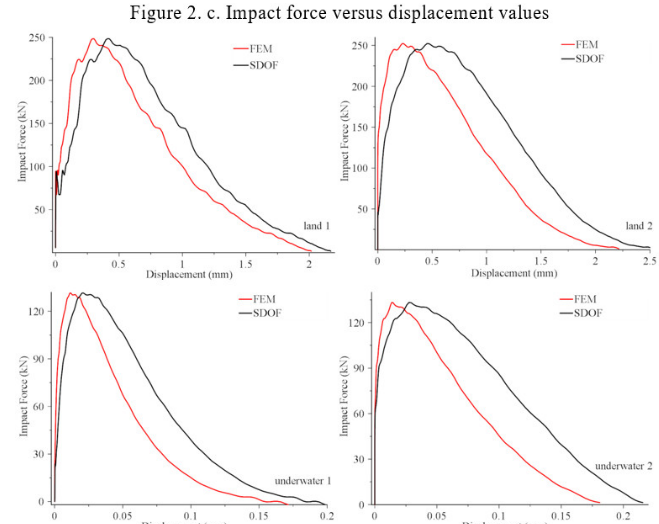


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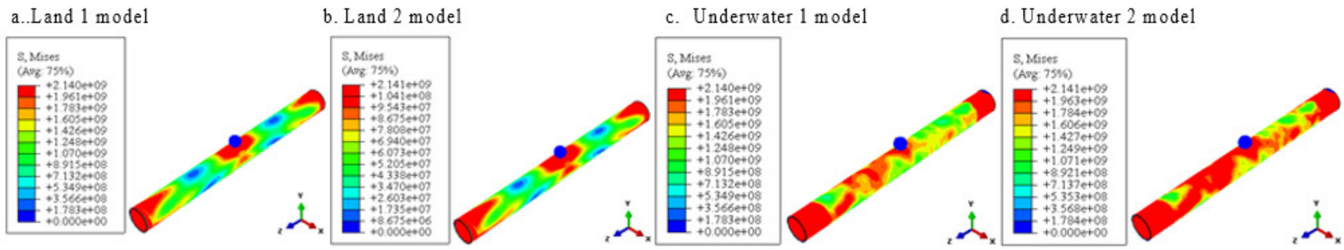
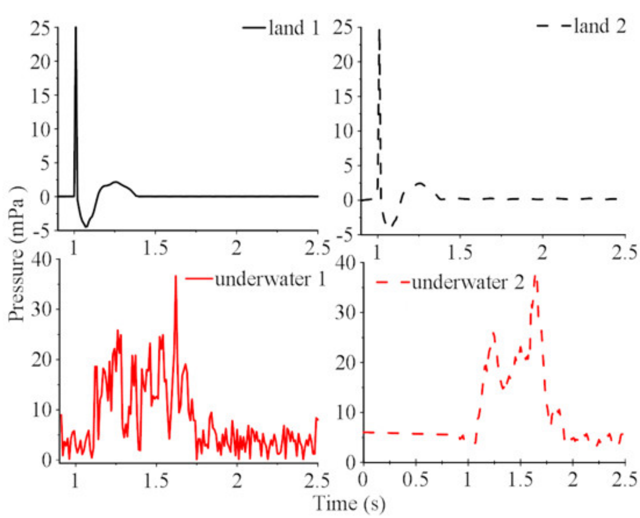
Figure 3: Stress distributions for the pipes.



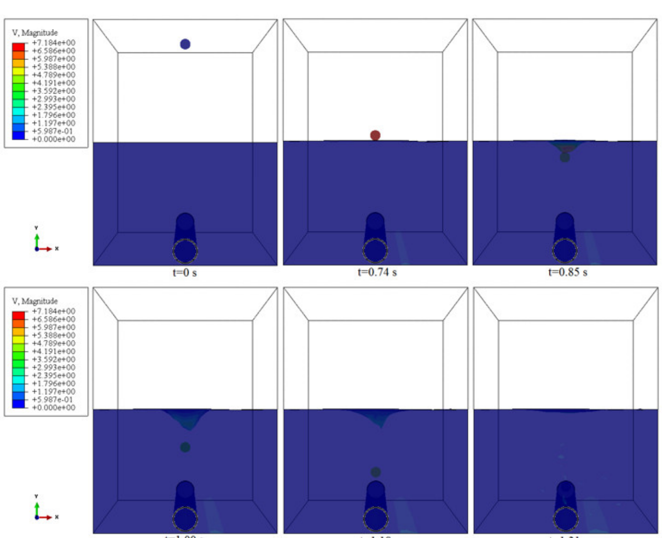
Source: Authors.

Figure 4: Time varying external pressure values of pipe models.



Source: Authors.

Figure 5: Velocity distribution of underwater pipe models.



Source: Authors.

height and mass of the striker on the empty and water filled land and underwater pipes. After completing the numerical analysis for each case, acceleration, velocity, impact force and displacement values are obtained from the software. Von-Mises stress distributions are determined after impact loading is completely transferred to the pipe members. Numerical values as well as surface movement of water are visually presented. In the semi-analytical analysis part of the study, SDOF analyses are performed to verify the analysis results. It is found out that a good relationship is established between both analyses.

The analysis results reveal that the impact behavior of the pipes is primarily effected by the water owing to damping. Maximum acceleration values have been determined from the water filled land pipe after both analyses. This tendency is also valid for the displacement and impact load values. The average and standard deviation values of acceleration and displacement are computed to allow comparison between the FEM and SDOF analysis results. A good correspondence between both of the results has been registered. Consequently, SDOF analysis could be used to evaluate the impact behavior of pipes at the design stage. When Von-Mises stress distributions are examined after numerical analysis, it is seen that maximum stress values are accumulated around the area where impact loading is implemented on pipes. Besides, stress values expand to the supports of the pipe members. Symmetrical stress distribution is obtained for land pipe models. It is also observed that bigger stress values that correspond to possible damages are determined for water filled pipe models. External pressure values reveal the effect of water on the underwater models.

The CEL procedure that comes through the deficiencies of the single Lagrangian and Eulerian methods enables modelling both fluid structure interaction and the free surface movement of the water. Surface of the water gets into motion due to the striker as shown in Figure 5 that present the changes in the water surface. It would be impossible to see the effect of water fluctuation in case the underwater pipe model was generated by only Lagrangian method or one-way fluid structure interaction.

As it is not always possible to perform experimental studies under impact loading due to the measurement limits of test setups, numerical and analytical solutions appear as significant options when accurate analysis conditions have been constituted. The accuracy of the results between numerical and semi-analytical analyses due to small error rates reveals that each procedure could be applied when investigating the impact behavior of structural members. Finally, it is concluded that this study is considered as a remarkable step towards the development of impact analysis in the computer environment.

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