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# 3Dimensional Indicator of Bulk Solid Pressures

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*Abstract:* - The paper investigates a bulk solid pressure observation inside a transport vessel using new developed 3Dimensional (Triaxial) Indicator. New design and conception of the 3D indicator have been developed exclusively for detecting of real stresses/pressures inside vessels, bunkers and silos. The unique design of the 3D indicator in cooperation with appropriate used software, and with a silo model is able to assure a clear image to pressure/stress identifications in particulate solid. Moreover, the real practice utilization for industry is in controlling of level material in transport vessels. Design and construction modeling of the 3D indicator have been presented in the paper.

*Key-Words:* - 3Dimensional indicator, bulk solid, transport vessel

## 1 Introduction

At present there is great emphasis being placed on the issue of ensuring safety and health in all areas of human activity. This issue particularly concerns the transport, handling and storage of all types of material used in transportation systems where people play an important and irreplaceable role. It must be kept in mind that these fields are nearly as old as mankind itself and represent a significant portion of national economies [2]. Problems that appear in this area have a major effect on the flow of material, as well as on the most important parameter for the operation of a company within the framework of its logistics. The most numerous problems-malfunctions occur during the storage and transfer of bulk material to another transport system (funneling, arching, creating an arch, core flow, etc. [5]). These malfunctions have an effect on the entire operation of the transport system, as well as on the subsequent lack of functionality that occurs in the entire system, which endangers operational safety [3,6].

In the past fatal injuries would often happen when the system operator, who was trying to ensure the flow of material from the storage system by use of mechanical means, would be buried during the fill. It is much better today with newly designed storage systems, and ensuring the continuous flow of material has become more efficient, making the problems mentioned above a rare occurrence. Still, there is a whole line of obsolete systems in use today with operating problems and it is very difficult to identify the location and nature of the malfunction in order to propose measures for ensuring the trouble-free operation of the system.

We normally encounter problems during the process of transporting, handling and storing bulk solids in silos and containers [8]. The problem increases for long-term storage due to the occurrence of undesirable incidents when filling and emptying stored solids. These incidents cause flow disruptions in storage systems as a result of the storage conditions, the effects of the surrounding environment and the generally natural and entirely unpredictable characteristics of bulk solids, the structure of the storage equipment, etc. For this reason, bulk solids, especially those with a powdery structure, are among the least predictable materials in relation to the above-mentioned incidents, to which factors involving their mechanical-physical properties (unconfined yield pressure, the angle of internal friction, etc. [9]), geometric properties (size distribution -e.g. fig. 1, etc.) and interparticle character [4], where it generally applies that the less particles there are, the more influence they have.

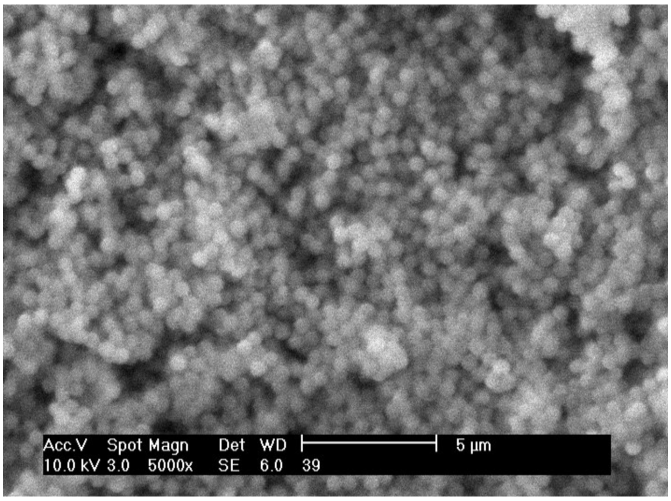

Fig.1. Size distribution of nano-structured Titanium Dioxide particles with a peak distribution about 600 nm.

The cube element (right) extracted from the silo for the bulk solid (left) with the stress points indicated on each of its walls.

In-depth research of the causes behind these failures, based on the precise identification of the stress in the bulk solid being stored, can result in the precise and long-lasting elimination of the character of the material that leads it to create the above-mentioned failures.

Even there are no adequate means for us to precisely detect the place and time of a possible failure. Today's commercially produced pressure (stress) indicators work in 2D and are situated on the perimeter of the cover for the storage equipment. This is the reason why the stress or pressure of the wall is often measured instead of the actual pressure of the bulk solid stored in the container.

For this purpose a 3Dimensional indicator for bulk solids (fig. 10, [9-11]) has been designed and constructed for allowing the actual stress in critical areas where the failures tend to occur to be detected. The change in stress (pressure), rather an increase in it, is the indication that a failure has occurred. Earlier indicators were based on the presumption that pressure and its fluctuations were transmitted to the wall of the container and for this reason they were located directly on the container (silo) wall itself. Unfortunately, this measurement often didn't reflect the real situation or the actual status due to the poor transmission of the signal from the source of the problematic material. The 3D indicator (fig. 8 and 10), including a methodology for identifying pressures using the SW developed for it, is able to completely solve these problems and, moreover, register all sudden occurrences that take place directly within the bulk solid.

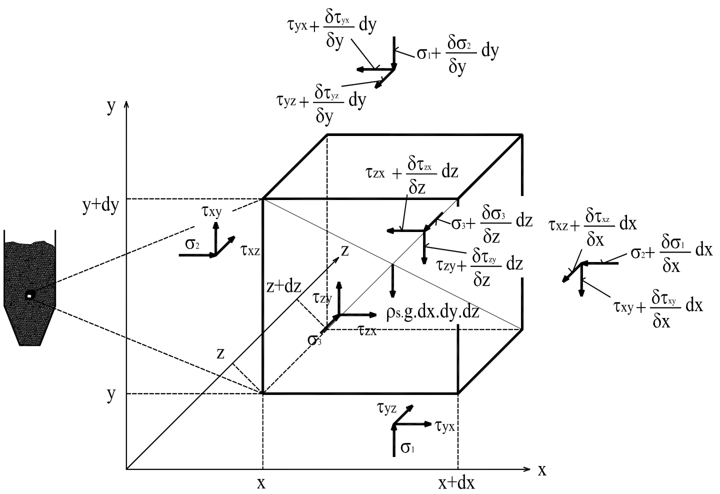

Fig.2. The cube element (right) extracted from the silo for the bulk solid (left) with the stress points indicated on each of its walls. Source: [9]

## 2 The theory of stress on an element of a bulk solid in cubic form in 3D mode

If we take into consideration an infinitely small element of a bulk solid in cubic form [7] removed from a container, one main normal stress is applied to each wall of the cube vertically and two shear stresses are applied in the corresponding directions (fig. 2) [9]. It must be noted that the stresses are major, i.e. the largest and they are expected to turn the extracted cube in the principal directions of *x*, *y* and *z* [9].

A total of 9 stresses are acting on the given cube (e.g. 3 normal $\sigma_1$, $\sigma_2$, $\sigma_3$ and 6 shear $\tau_{xy}$, $\tau_{xz}$, $\tau_{yx}$, $\tau_{yz}$, $\tau_{zx}$, $\tau_{zy}$), of which 3 shear stresses, moreover, are compounded, giving us $\tau_{xy}=\tau_{yx}$, $\tau_{xz}=\tau_{zx}$ and $\tau_{yz}=\tau_{zy}$.

Given the assumption that the shear stresses are compounded (e.g., $\tau_{xy}=\tau_{yx}$, $\tau_{xz}=\tau_{zx}$ and $\tau_{yz}=\tau_{zy}$), an equation for the cube element can be thus expressed from an equalized state:

$$(\partial\sigma_2/\partial x)+(\partial\tau_{xy}/\partial y)+(\partial\tau_{xz}/\partial z)=0 \qquad (1)$$

$$(\partial\sigma_1/\partial y)+(\partial\tau_{xy}/\partial x)+(\partial\tau_{yz}/\partial z)+\rho_S.g=0 \qquad (2)$$

$$(\partial\sigma_3/\partial z)+(\partial\tau_{xz}/\partial x)+(\partial\tau_{yz}/\partial y)=0 \qquad (3)$$

Mutual dependency and a linkage between the shear stresses in all directions are the result of these relationships. We get 3 relationships that describe the behavior of the bulk solid element in 3 directions under the assumption that normal stresses $\sigma_1$, $\sigma_2$, $\sigma_3$ and shear stresses $\tau_{xy}$, $\tau_{xz}$, $\tau_{yz}$ are at work. By modifying the relationships (1 of 3) e.g. their partial derivative ($\partial/\partial$x) (1), ($\partial/\partial$y) (2), ($\partial/\partial$z) (3), multiplying (-1) the relationships (2) and (3), and subsequently adding up the relationships (1 to 3), we get only one equation (4) describing the state of stress of the bulk solid in the 3D picture.

$$(\partial^2\sigma_2/\partial x^2)-(\partial^2\sigma_1/\partial y^2)-(\partial^2\sigma_3/\partial z^2)-2(\partial^2\tau_{xz}/\partial x\partial z)=\gamma_S(\partial/\partial y) \qquad (4),$$

where $\gamma_s$ is the weight density of the bulk solid (constant quality), defined as

$$\gamma_s=\rho_s\cdot g \qquad [\mathrm{N.m^{-3}}] \ (5),$$

It's normal in publications [5] to give the relation $\gamma_s=\gamma_s(\sigma_1)$ *and* $\rho_s=\rho_s(\sigma_1)$, thus the relation (4) can be modified:

$$(\partial^2\sigma_2/\partial x^2)-(\partial^2\sigma_1/\partial y^2)-(\partial^2\sigma_3/\partial z^2)-2(\partial^2\tau_{xz}/\partial x\partial z)=$$
$$=g.(\partial\rho_S(\sigma_1)/\partial y) \qquad (6),$$

The equation (6) explains the relation of the state of stress of the bulk solid in view of the mechanical-physical property of the stored material. The state of stress of the bulk solid in the form of stresses $\sigma_1$, $\sigma_2$, a $\sigma_3$ is reflected by the mechanical-physical property of the bulk solid in the form of the weight density $\gamma_s$. It therefore applies that the weight density of the given bulk solid is shown principally by the normal stresses $\sigma_1$, $\sigma_2$, $\sigma_3$ at work, but also by the shear stress $\tau_{xz}$ at work in the equation *x*, *z* (see fig. 2).

Important from the view of the effect and identification of the measurement are the normal stresses $\sigma_1$, $\sigma_2$, $\sigma_3$ in the axes *x, y* and *z*. The stress at work in the bulk solid has an effect on the deformations, which are the main indicators of the behavior of the bulk solid.

We furthermore express the yield coefficient *k* for individual ratios of the normal stresses $\sigma_1$, $\sigma_2$, $\sigma_3$ in accordance with fig. 2, thus

$$k_{23}=\sigma_3/\sigma_2=(\sigma_{S23}-R_{23})/(\sigma_{S23}+R_{23})=(\sigma_{S23}-\sigma_{S23}.\sin\varphi_{23})/(\sigma_{S23}+\sigma_{S23}.\sin\varphi_{23}) \quad [\mathrm{N.m^{-3}}] \tag{7}$$,

where $R_{S23}=(\sigma_2-\sigma_3)/2$ and $R_{S23}=(\sigma_2+\sigma_3)/2$.

Similarly for other ratios of stress

$$k_{12}=\sigma_2/\sigma_1=(1-\sin\varphi_{23})/(1+\sin\varphi_{23}) \tag{8}$$,

$$k_{13}=\sigma_3/\sigma_1=(1-\sin\varphi_{13})/(1+\sin\varphi_{13}) \tag{9}$$,

then it applies that

$$k_{13}=k_{12}.k_{23} \tag{10}$$,

and the mutual relation of normal $\sigma_1$, $\sigma_2$, $\sigma_3$ under the assumption of a constant yield coefficient $k_{12}$, $k_{23}$ and $k_{13}$ can be expressed as

$$\sigma_2=k_{12}.\sigma_2 \tag{11}$$,

$$\sigma_3=k_{13}.\sigma_1=k_{12}.k_{23}\sigma_1 \tag{12}$$,

and their partial derivative:

$$(\partial^2\sigma_2/\partial x^2)=k_{12}(\partial^2\sigma_1/\partial x^2) \tag{13}$$,

$$(\partial^2\sigma_3/\partial z^2)=k_{13}(\partial^2\sigma_1/\partial z^2)=k_{12}.k_{23}(\partial^2\sigma_1/\partial z^2) \tag{14}$$,

By modifying the relationships, e.g. by achieving (13) and (14) to (6) we get:

$$k_{13}.((\partial^2\sigma_1/\partial x^2)-k_{23}(\partial^2\sigma_1/\partial z^2))-(\partial^2\sigma_1/\partial y^2)-2(\partial^2\tau_{xz}/\partial x\partial z)==g.(\partial\rho_S(\sigma_1)/\partial y) \tag{15}$$,

The dominant effect of the main normal stress $\sigma_1$ for all the directions *x, y* and *z* stems from the preceding relation (15) under the assumption that a constant yield coefficient as given by the ratios in the principle directions (13, 14) apply.

This supposition, together with the basic element of the bulk solid (fig. 2), led to the construction of a 3D indicator [9] able to read all normal pressures in the appropriate directions of *x*, *y* and z [10] by measuring the deformation of the component embedded in the bulk solid.

## 3 The history of determining the status of stress in a bulk solid with three-dimensional devices

The absolute first device connected with researching multiple stresses in bulk solids was designed by Kjellman (1936). It was a device with a general state of stress (fig. 3) able to deform a bulk solid cube and observe the state of its stress. The device consisted of panels from a hard material or membranes sealed with various means (fig. 3). During individual research into the behavior of the bulk solid, the cube-shaped device was embedded between membranes, put under stress in one, two or three directions, and its behavior was observed during the transformation, e.g. whether a separate deformation in individual directions would be observed under a set triaxial load or there would be combined research, i.e. operating with a known stress loaded in one direction and determining the deformation and stress characteristics in the other directions.

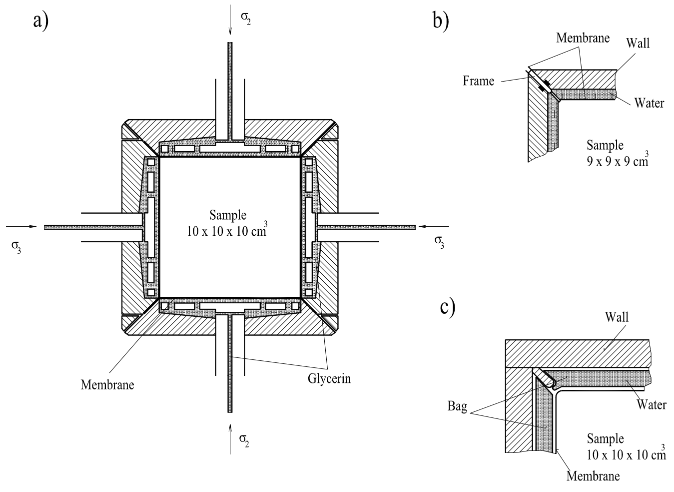

Fig.3. The device with a general state of stress according to a) Kryzanov and Lomise 1961, b) modifications by Ko and Scott, 1967, c) design changes by Arthur et al. [1]

The most important questions for devices working under a universal state of stress were raised with a view to determining the maximum amount of stress that could not be transferred from one loaded membrane to another loaded membrane. For this purpose several design modifications were carried out on the periphery (fig. 3 and b) with one goal in mind – to prevent the transfer of shear forces and the mutual effects of stress during testing. This prevention has been successfully resolved within the limits of feasibility in fig. 3 c).

The basic principle of operation for a cube-shaped device subjected to a change in the status of stress under load is pictured in fig. 4. The entire equipment consists of a setup of smoothly polished movable panels able to move without any problems. These individual panels create something like “membranes” allowing research to be done on changes in stress and deformation using a detector located on the surface of the panels in three perpendicular directions.

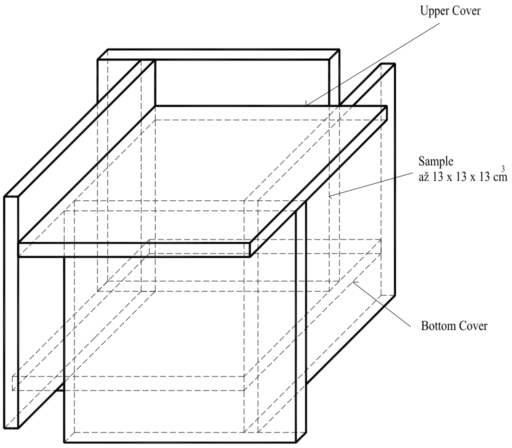

Fig.4. The basic principle of the device under a universal state of stress according to Hambryh (1970). Source: [1]

## 4 The construction and development of a 3Dimensional (Triaxial) device for observing the state of stress

Current development in devices used for measuring the state of stress in bulk solids has stagnated and brought with it no major new innovations in the field for developing entirely new measuring equipment. The equipment developed in the past few years has moved the opportunities for discovering flow failures in bulk solids forward, but they are based on concepts from similar equipment developed in the 1960s and 1970s (FT3 Powder Rheometer-see Propeller test [9], etc.).

The first sign of progress in this field was a study of a model allowing triaxial stress to be observed in storage systems (see fig. 5) and the most current status in the bulk solid to be recorded in random locations in the storage system. This model was first set up in Gainesville, SSIW 2003, at the University of Florida, USA. This “purely theoretical” model is able to observe all 18 shear and normal stresses occurring on the element of the bulk solid using indicators embedded in the structure (see fig. 5) and afterwards on the surface of the cube representing the load-bearing basic structure of the entire equipment.

### 4.1 A 3Dimensional (triaxial) measuring apparatus developed at the Laboratory for Bulk Solids within the framework of Post.-Doc. grant 101/03/D039

The design of the model (fig. 5), unfortunately, was not completed principally due to the practically impossible ability to detect all 18 various (combined) shear and normal stresses and their subsequent intricate interpretation. This proved to be the call for designing an entirely newly conceived and different model able to observe only the main state of stress in the form of main normal stresses ($\sigma_1$, $\sigma_2$, $\sigma_3$) and subsequently deriving the shear stresses and picturing the state of stress of the bulk solid being observed in the storage equipment, including a theoretical analysis of the state of stress (chap. 2).

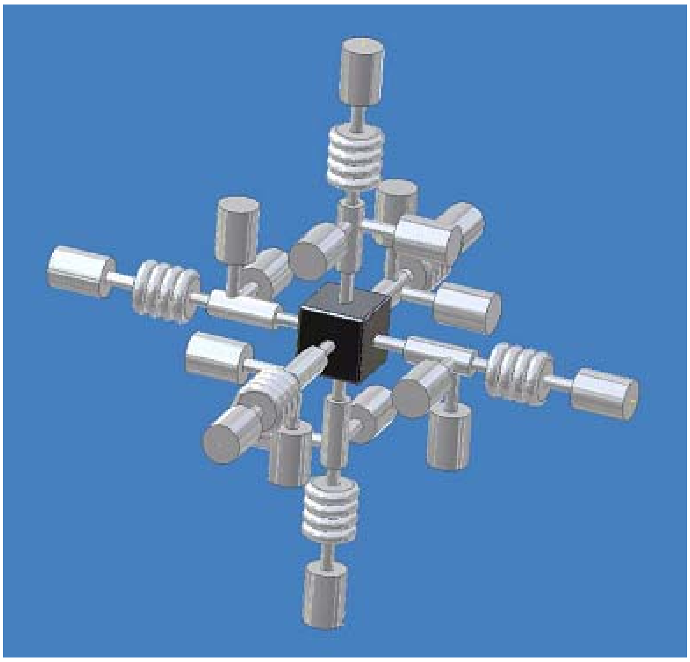

Fig.5. Model fully describing the state of stress of all normal and shear stresses acting on the element of the bulk solid. Source: SSIW, the University of Florida, Gainesville, 2003.

Economical factors were also taken into account and only those components necessary for designing and setting up the model were selected, even with regard to using the minimum amount of detectors.

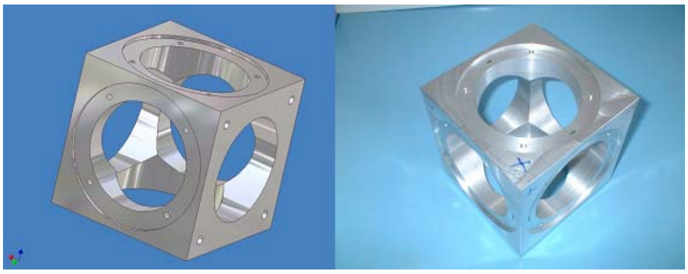

Fig.6. Computerized design of a model of a cube (left) and the produced shape of the cube (right). Source: [9]

When considering the structure of the model by itself, the need for a hard base was taken into account for individual detectors with the goal of decreasing deformation effects as much as possible for the individual load-bearing structure of the base for the measuring apparatus embedded in the bulk solid of the storage system. For this purpose a load-bearing base for the cubed shape was designed (fig. 6) from the initial inspiration of a theoretical state of stress (fig. 2).

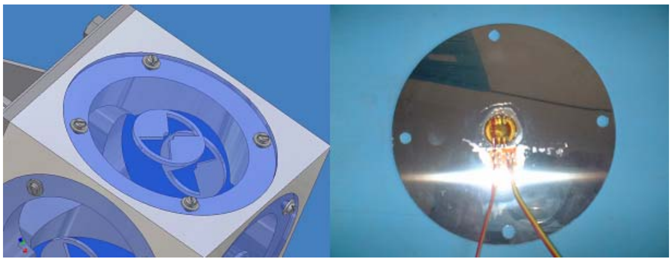

Fig.7. A computerized model of an embedded deformation component with deformation detector (left) and the manufactured deformation component, including the location of the detector (right). Source: [9]

The base of the cube was equipped with an attachment (fig. 6) for the purpose of embedding four deformation faces (fig. 7 right, fig. 9) using cylindrical screws. The deformation face was designed in a circular shape in order to capture deformation on the axes of *x*, *y* and *z* and afterward check the deformation on the *y* axis (a total of 4 faces). This shape meets the right criteria for symmetrical deformation and the radial and tangential voltage stress for locating the deformation detectors (tensometric sensors) precisely in the middle of the internal wall of the deformation face.

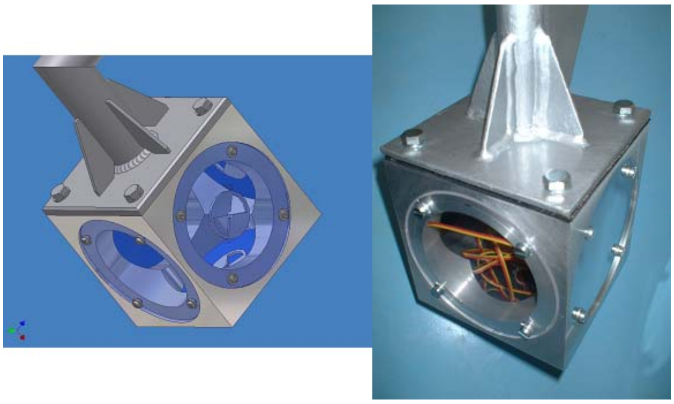

Fig.8. Computerized design of the model setup with indicators and attachment (left) and mounted 3D indicator (right). Source: [9]

The deformation faces were made out of a stainless material with an alloy of refined components (phosphorus, etc.) in order to ensure elastic deformation without creeping effects all the way up to the limits of the proportions of the deformation material of the face (fig. 7-9). The internal orifice of the load-bearing base of the cubed shape (fig. 6) milled out with other orifices for the deformation faces was used for locating the structure of the detectors and amplification components of the deformation detectors, including transmitting their supply and the signals of the deformation stress via the embedded load-bearing structure.

Fig.9. The load-bearing base of the cube with four deformation faces furnished with deformation detectors (tensometric sensors) connected to the full bridge. Source: [9]

## 5 Conclusion

The designed 3D indicator (Fig. 10), including the methods for identifying the pressure of bulk solids using the appropriate SW, is able to solve flow problems that occur within the entire scope of the storage equipment and, what's more, it can register all immediate occurrences directly in the space of the bulk solid being monitored.

Fig.10. The 3Dimensional detector assembling for bulk solid observations. Source: [9]

The significant contribution of the doctoral candidates who were engaged in finding a solution for the equipment from its earliest conception until it was carried out led to the creation of an adept team of capable people who were willing to participate in the development of the equipment as a whole, and to design and improve the solution for the equipment. The future of this entire team of developers depends on the support of further research assignments within the scope of the Czech Science Foundation and other scientific foundations. Today there is a real chance for doctoral candidates to work within the scope of projects from CIPT – the Center for Information on Advanced Technologies – founded at VŠB – Technical University of Ostrava.

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