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A POWERFUL METHOD FOR STRESS ANALYSIS: THE PHOTOELASTICITY METHOD – SOME EXAMPLES FROM THE ITU EXPERIMENTAL MECHANICS LABORATORY

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Abstract. Stress analysis is a crucial step for a design or strength analysis. The methods of experimental analysis are indispensable for validation when the approximations in the analytical and numerical methods are taken into account. As one of the first experimental methods, photoelasticity offers a very useful way to analyze different models of transparent material. Not only two-dimensional stress analyses are performed with this method, but also a full three-dimensional analysis can be performed with the strain-freezing method based on the viscoelastic property of the material used. In the Experimental Mechanics Laboratory at Istanbul Technical University (ITU), various models from different research areas are produced and analyzed, from civil engineering to biomechanics or mechanical engineering to dental technology. This presentation summarizes some of the interesting experiments carried out in this laboratory.

Keywords: stress analysis, experimental analysis, validation of numerical methods, approximations, experimental mechanics

1.Introduction. An object that is exposed to external forces is subjected to certain deformations, which can be measured with special tools. During this deformation, the material of the object exhibits the result of the deformation, the so-called stress. Although it is a physical quantity, stress is defined in mechanics as an imaginary phenomenon with the force per unit area. It is not possible to visualize or to measure stress or its components. In terms of the continuum assumption, a material point is assumed to be under a state of stress, which is assumed to be a continuous variable over the volume of the object [1-3]. Engineers or designers need a comparative tool to evaluate the strength of their design and the stress with the quantity of strain, simply the unit deformation, is used as data for this evaluation. The stress state is predictable when the geometry and loading are not complex. However, in complex cases, as in most cases in nature, this state must be determined in order to explain the behavior of the object or design.

The theory of elasticity provides analytical methods for determining the stress field [1-4]. The difficulties in applying the solutions have been overcome by numerical methods. In this way, predictions can be made for many different complex problems. However, the predictions suffer from the degree of approximation, and one cannot say anything about the degree of approximation if one does not know the absolute solution. In fact, who can say that there is only one absolute solution to a case in nature, because no one guarantees that everything in the problem under consideration exists in the same way at all times. Nevertheless, the experimental methods with the simplified conditions provide the most reliable results for a given problem. Therefore, a validation of the analytical and numerical methods can be made on the basis of the experimental results [6, 7].

Validation brings accuracy to the proposed solution, and it can be done with a reliable method of analysis. In analytical modeling, there are some approximations and idealizations to construct the

equations. Moreover, the exact solutions of the analytical equations can only be obtained for very limited simple problems. Numerical solutions help us to solve complex problems, but there are many problems with this solution, such as rounding error, convergence, etc. Experimentation is an important way to validate the results of numerical or analytical analysis of a structure. Validation can be performed effectively if the experimental method and conditions for the experimental setup are properly defined, and the measurement instruments do not disturb the stress field of the model.

Photoelasticity is an experimental method based on the birefringence of light by an optically sensitive material under external loads. This method establishes a relationship between the optical anisotropy of the material and the stress distribution. Optically anisotropic materials refract light in two directions perpendicular to each other at different velocities when they are loaded. The difference in velocity varies from point to point depending on the stress value. The dark-field arrangement with two polaroid filters and two quarter-wave plates in a circular polariscope (Fig. 1) enables the fringe patterns of isochromatics with integer orders on a transparent model such as Araldite, an epoxy-based resin, as a result of the loading conditions. This is because the order is determined by the phase difference between two light components generated by the birefringence property of the material. The material is called an optically anisotropic material, which means that it refracts the light in two directions perpendicular to each other when it is loaded. The retardation is the result of the difference in the velocities of these perpendicular light components. One can view color patterns with different darknesses. In the dark-field arrangement, these color patterns, isochromatics, show the points where the difference of the in-plane principal stress is the same. In other words, along an isochromatic pattern, the difference of the in-plane principal stresses, $\sigma_1 - \sigma_2$, is a constant and the result of the order of the pattern. The relation is expressed as follows:

$$\sigma_1 - \sigma_2 = f_{\sigma} \frac{N}{h} \quad (1)$$

where f_{σ} , N and h are material fringe value, the order of the fringe pattern and the model thickness parallel to the light direction [5-7].

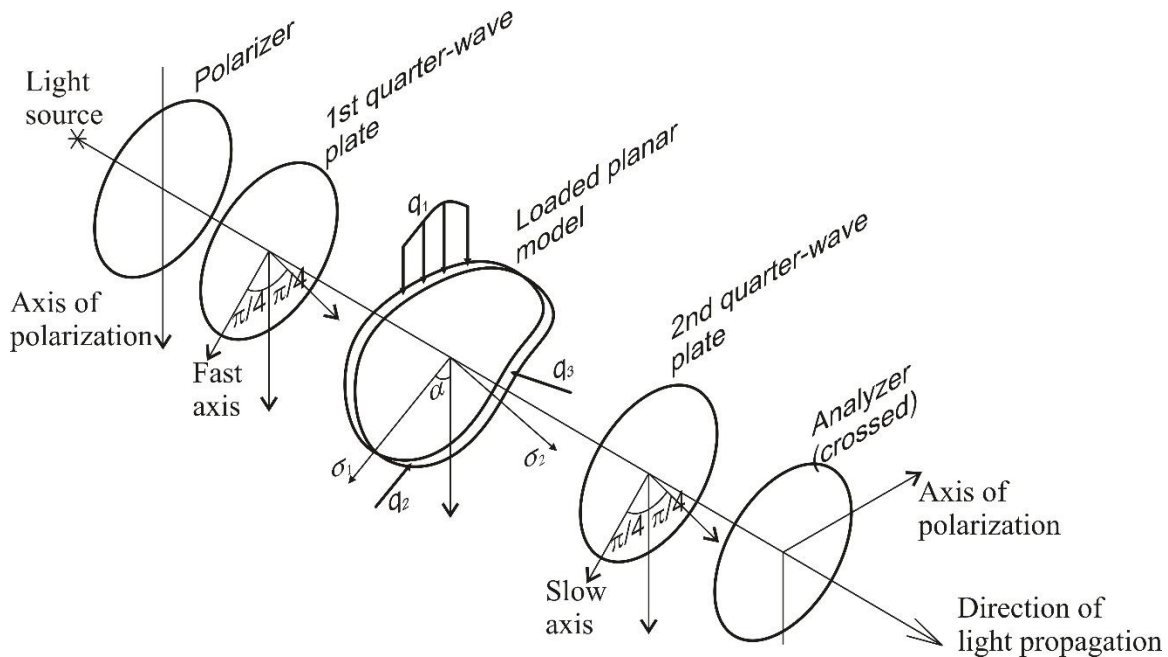


Fig. 1. The dark-field arrangement with two polaroid filters and two quarter-wave plates in a circular polariscope

In Fig. 1, the dark-field arrangement of a polariscope is shown. The stressed model has a very small thickness compared to its other dimensions. This arrangement reveals the planar real-time stress distribution over the entire observed field of model. As can be seen in Eq. (1), the order of the isochromatics gives the difference of the planar principal stresses. In order to separate the principal stress, an additional equation is required.

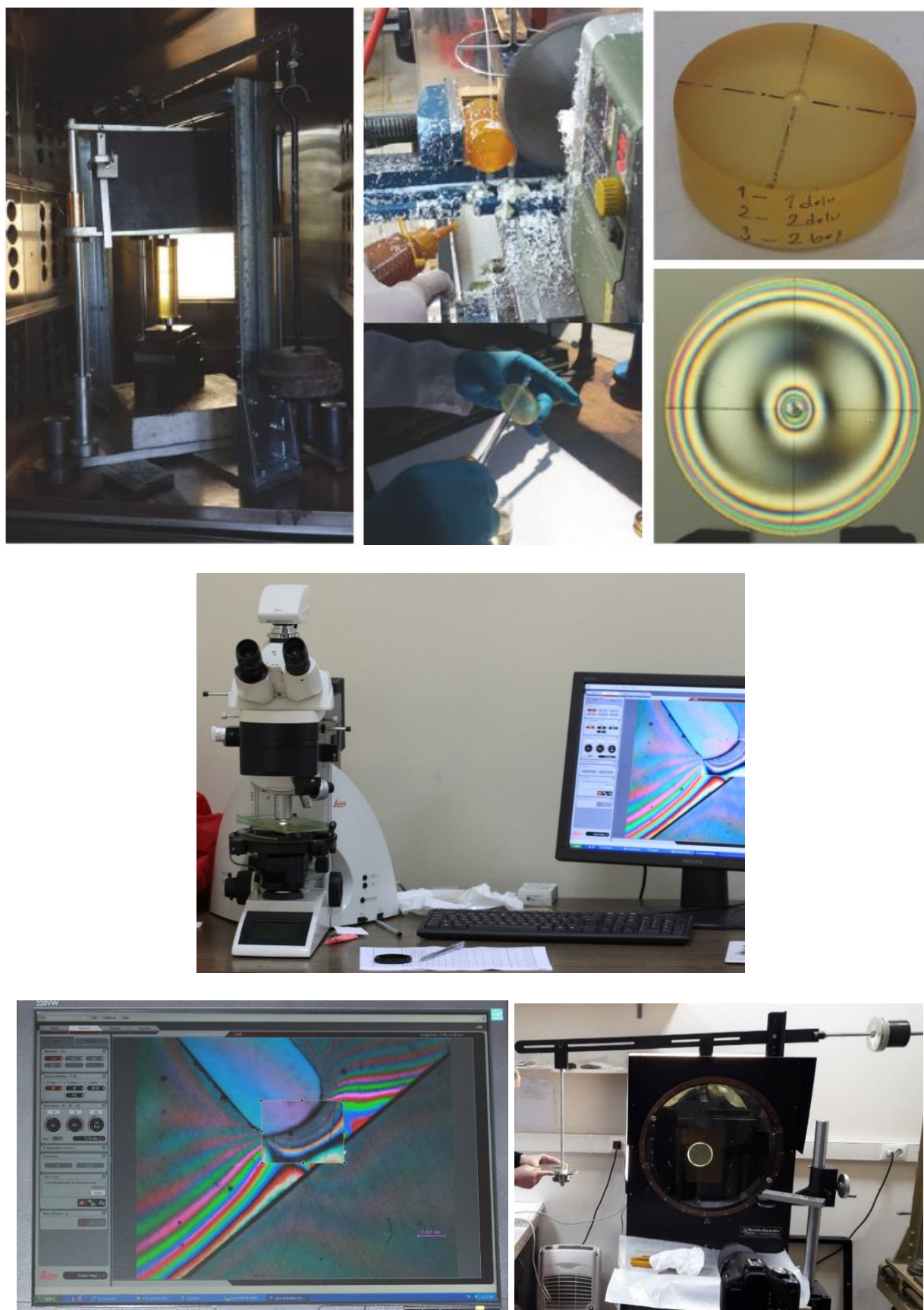


Fig. 2. Real time loading and stress analysis; strain-freezing method and taking slice; the analysis of isochromatics around the tip of cavity using polarized microscope

To derive this, several techniques have been developed in the literature. These can be used to determine the in-plane principle stresses. The directions can also be determined using isoclinic fringe patterns obtained with different arrangements of the polarisation filters. Once the state of stress for the model is determined, one can obtain the state for the prototype. It is known from the theory of elasticity that the stress field does not depend on the material properties if the body forces are neglected. In this respect, the determination of the state of stress is very valuable for the analysis. The stress distribution is related to the linear-elastic deformation. Due to this, the distribution of fringe patterns is recorded using a high-resolution camera. However, the third component of stress cannot be determined with this technique. Therefore, the models in this technique are generally plate-shaped. A 3D analysis is possible with the strain freezing method in the experiments [8-18].

In the strain freezing method, a transparent polymer material, which is linearly elastic at room temperature is heated to a temperature above the glass transition temperature, at which the material behaves linear-elastic with a lower value of the constant modulus of elasticity. The load applied to the model leads to the strain distribution related with this elastic modulus. When this model is gradually cooled, which is necessary to avoid residual stresses in the material due to the temperature change, this strain distribution is fixed in the model. The deformed shape of the model does not change, even if the loads are removed. These deformations are not the result of plastic behavior. The 3D stress analysis can be carried out taking slices from the designated points.

In Fig. 2, a real-time planar loading setup and the application of strain-freezing method are shown. The analysis of isochromatics near a singularity point is difficult and a polarized microscope is used to see the fringe patterns clearly. This microscope has a unit of Berek compensator that is used to measure the phase difference of light components.

In this work, the advantages of the method of photoelasticity are explained using the application examples from the Experimental Mechanics Laboratory at Istanbul Technical University.

2. Determination of the dynamic change in stress at the tip of a cavity. A long plate was axially loaded by a dynamic tensile force (Fig. 3). There were two closed cavities in the centre. The geometries are identical for these cavities. After an initial static load, a dynamic load was applied. A high-speed camera was used for the setup as shown (Fig. 4). The change in the isochromatic fringe distribution was recorded during the dynamic exposure (Fig. 4).

During dynamic loading, the change in the fringes was recorded by a camera. Since the recording rate of the camera and the resolution are low, the video shows the change abruptly. If the capacity of the camera is increased, the dynamic change of the fringes can be clearly visualized. This is intended for the determination of the dynamic stress distribution during crack initiation [17].

3. The stress distribution in underground pipes considering water saturation. The soil-pipe interaction was also investigated using the method of photoelasticity in the Experimental Mechanics Laboratory. For this purpose, a new setup was developed as shown in Fig. 5.

This setup allows a non-intrusive stress analysis without disturbing the soil field. Moreover, water can be added to the system, which increases the saturation of the soil. The pipe is modelled as a plain strain element in these tests.

Different types of soil were tested in this setup to understand the effect of the particle shape. In Fig. 6, two types of soil are given. The geometry of the soil grains are captured with a microscope. As it is seen, the sample on the top has more rounded grains than the sample on the bottom (Fig. 5). In order to understand the effect of the water level in the soil on the stress distribution in the pipe model, the water is manually controlled in the setup. The water level in the soil and the isochromatic fringe distribution in the pipe model are shown in Fig. 6 [11].

4. Conclusion. Photoelasticity is a very powerful method for analysing stress distribution. In this article, some examples of stress analysis performed in the Experimental Mechanics Laboratory in Istanbul Technical University (TU) are presented. There are many such example applications presented in the literature by this laboratory. Especially, some applications focus on the 3D stress analysis. The 3D stress components can be determined using the strain freezing method. The method can be applied to a variety of technical problems in future work. The method is superior to other methods because the entire stress state can be considered in the model. Experimental Mechanics Laboratory is ready to

collaborate on this this type of stress analysis.

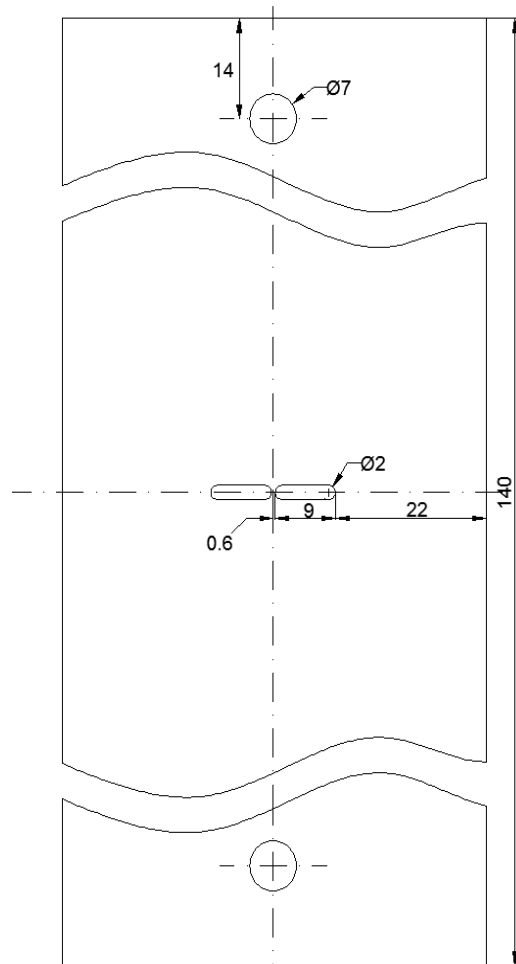
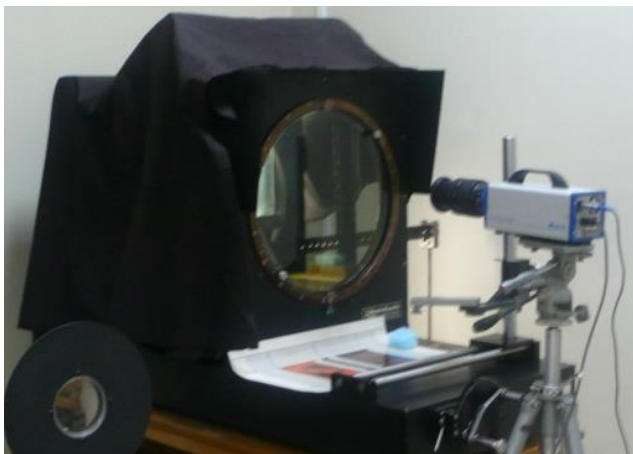
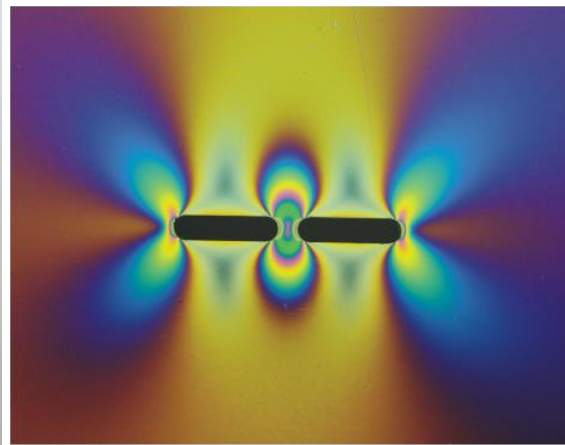


Fig. 3. The sketch of the model



(a)



(b)

Fig. 4. (a) The setup for the dynamic loading, the high-speed camera is utilized to catch the variation of stress concentration around the tips; (b) a picture taken from the model under load, the stress concentrations are seen around the outer tips and the interaction between the cavities are visualized

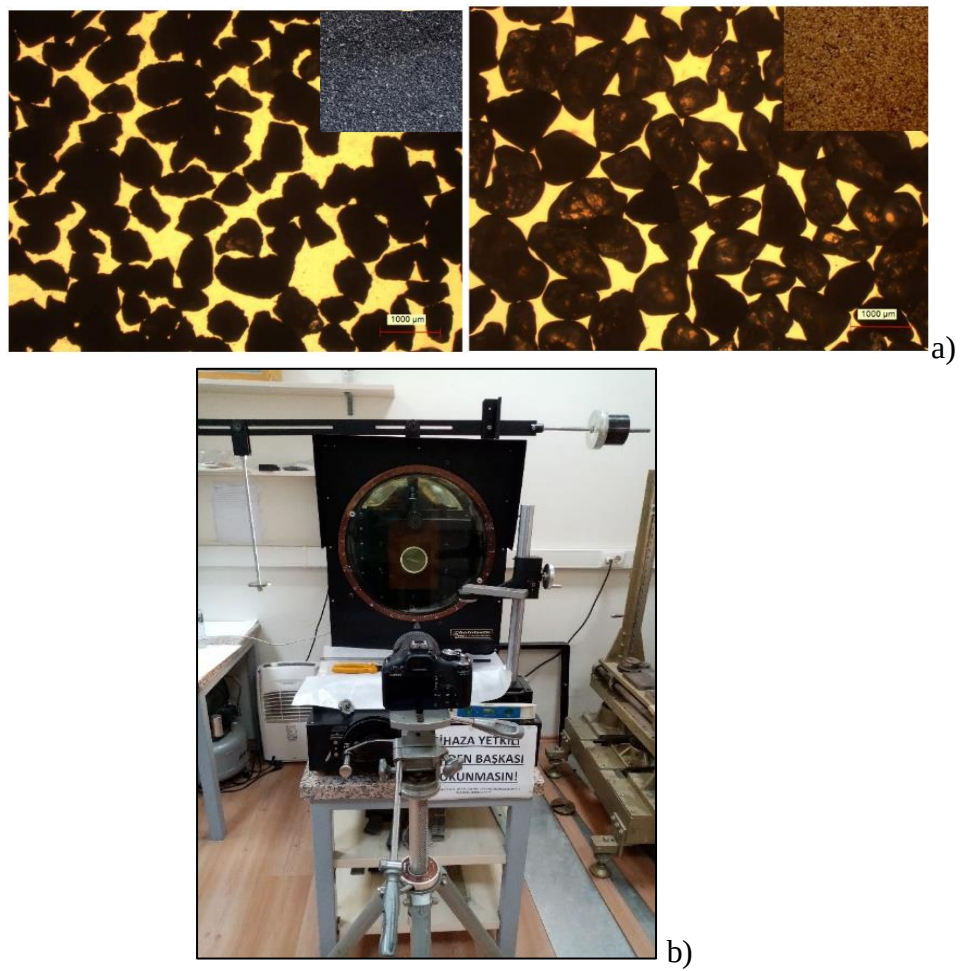


Fig. 5. (a) An original setup for the investigation of stress distribution in a buried pipe, (b) Views of the samples under the polarizing microscope with 16× magnification and with the naked eye

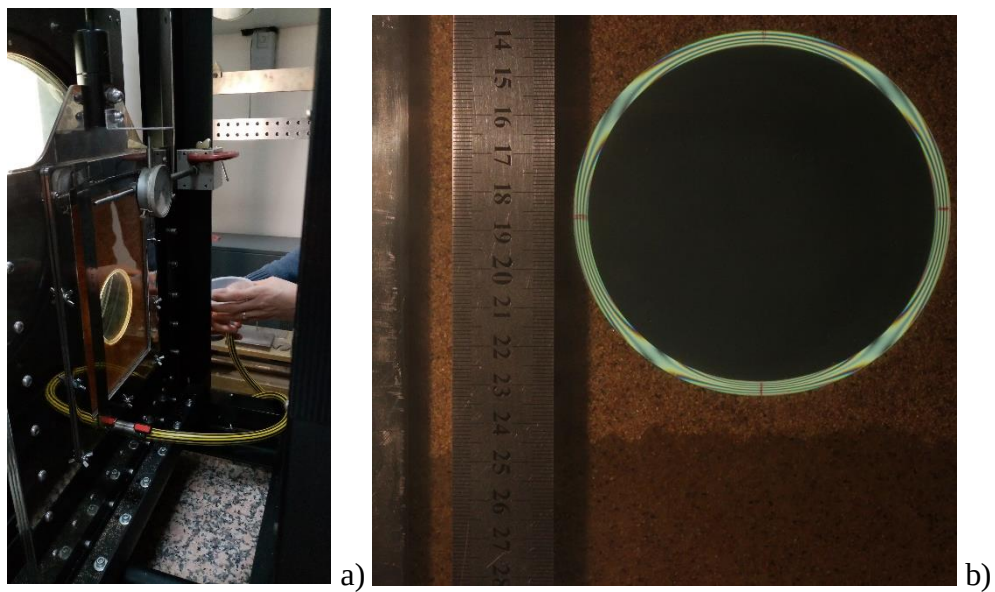


Fig. 6. (a) Changing the water level in the soil field, (b) a stress distribution in the pipe in the model

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