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Parameter studies of statically tilted unanchored cylindrical tanks

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ABSTRACT

In recent years many thin-shell cylindrical tanks have been damaged during earthquakes. The seismic uplift response problem of unanchored tanks has been studied under the simpler static tilt condition. This paper quantifies the sensitivity of the uplift behaviour to some of the important paramters which characterize the tank system, namely, the tilt angle, the height-to-radius ratio, the tank shell and bottom plate thickness, the stiffening effect of the top rim wind girder and bottom toe ring, and the roof type. The discussion on the uplift resistance mechanism is based on the response quantities related to observed seismic tank damage, such as the vertical uplift displacement, the extent of uplift in the bottom plate, and the tank shell membrane and bending stresses near the base.

INTRODUCTION

Thin shell cylindrical tanks are very efficient structures, and have applications in almost every major industry. They are simple in form and relative easy to construct. However, in recent years, many cylindrical tanks have been damaged during earthquake, sometimes with serious environmental ramifications, thus raising concerns about the seismic safety of these structures.

In the design standards AWWA (1984) and API (1988), which cover the design and fabrication of welded cylindrical steel tanks, the static strength design is based on the allowable hoop stress from the membrane theory. However, the seismic behaviour of cylindrical tanks is very different from the static behaviour, in particular for the unanchored ones. The seismic resistance mechanisms involved were not until recently fully understood. Based on field studies of seismic damages (Benuska ed. 1990), and observations from shaking table tests (Manos and Clough 1982), it has been determined that an unanchored tank uplifts significantly at the edge when subjected to even moderate horizontal base motion. When the tank liquid content is subjected to horizontal strong ground motion, hydrodynamic forces are generated acting on the tank wall and bottom plate, in addition to the hydrostatic pressure. A lateral resultant force and overturning moment develops at the tank base due to the liquid inertia effect and sloshing, and the tank uplifts on one side in response to this overturning moment.

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STATIC TILT UPLIFT

In general, the dynamic uplift mechanism of an unanchored tank is a very complex nonlinear problem. Recognizing the many uncertainties in the seismic behaviour of cylindrical tanks, the uplift problem has been studied here under the simpler static tilt condition (Clough and Niwa 1979, Manos and Clough 1982, Lau and Clough 1989, Peek 1986, Haroun et al. 1990) produced by tilting the support platform from its initial horizontal position as shown in Fig.1. The partially filled tank thus is subjected to an effective static lateral acceleration component which simulates the effect of the horizontal acceleration component of an earthquake. The resultant static lateral force and overturning moment caused uplifting of the unanchored tank on one side, as shown in Fig.2. This deformation has all the important characteristics of the dynamic uplift response, and makes it possible to develop understanding of the uplift mechanism involved. As noted in the figure, there is separation of the bottom plate from the supporting foundation even on the contact side, because of the base joint rotation caused by the hydrostatic pressure pushing out on the tank wall. A similar condition applies axisymmetrically around the tank bottom in the initial horizontal position. Details of the static tilt uplift behaviour have been discussed in an earlier paper (Lau and Clough 1989).

This paper quantifies the sensitivity of the uplift behaviour to various parameters characterizing the tank system based on the study of the static tilt uplift model.

METHOD OF ANALYSIS

The tank system considered in the present study consists of a cylindrical shell of radius a and height t_l, partially filled to a depth of d_w. The thickness of the cylindrical shell and the bottom plate are h_t and h_b respectively. As specified in the design standards, the bottom plate protrudes 2 in. (50.8 mm) outside the shell wall. The cylindrical tank also has a top rim stiffening wind girder. The support platform is statically tilted to an angle ϕ with the horizontal plane.

An effective analysis procedure based on the substructure concept has been developed to study the static tilt behaviour. Putting the method in the finite element context, the uplifting cylindrical tank is divided analytically into substructure super elements, namely the cylindrical shell, the bottom plate, the top wind girder and the bottom toe ring. Each element is formulated by Ritz discretization using derived displacement shape functions. Large displacement theory is employed in the modeling of the bottom plate, of which both the membrane and flexural mechanisms are considered. A nonlinear equilibrium equation is obtained by applying the principle of virtual work, which is then solved by iteration using current updated tangent stiffness. The bottom plate contact pattern is also established by iteration. The details of the formulations can be found in the references (Lau and Clough 1989; 1990).

PARAMETER STUDIES

In general, the geometry of a cylindrical tank is characterized by its height-to-radius (aspect) ratio. The top may be open with a flexible floating roof, or it may have a fixed welded roof typically of conical shape. The flexibility of the tank system is related to, in addition to the tank geometry, the plate thickness and the stiffening effect of the wind girder.

The critical parameter variations considered in the present study are the height-to-radius ratio, the plate thickness of both the tank shell and the bottom plate, the roof type and the stiffening effect of the wind girder and bottom toe ring. The influences of these parameters on the uplift behaviour of unanchored tanks are studied.

Tilt Angle

The static uplift loading, induced by tilting the tank rigid support platform, is directly related to the tilt angle, which may be looked upon as related to the intensity of the ground motion in the dynamic case. Therefore by increasing the tilt angle in static tilt analysis, the results obtained should give an indication about the sensitivity of the unanchored tank uplift mechanism to the ground motion intensity.

Static tilt uplift analysis results are presented for a broad 1/3 scale welded aluminum model tank, tested in a previous investigation (Manos and Clough 1982). The model tank, denoted here as the standard case, is 0.08 in. (2.03 mm) thick, 12 ft. (3.66 m) in diameter and 6 ft. (1.83 m) high, with a height-to-radius ratio of one. In the present study, the static tilt angle varies from 0 to 16 degrees with 5 ft. depth of water in the tank.

The variations with tilt angle of the maximum base uplift (Pt.A in Fig.2), the extent of the bottom plate uplift (e in Fig.2), the tank shell membrane stresses at the contact pivot point (Pt.B in Fig.2), and the bending stresses on the uplifted side (Pt.A in Fig.2), are presented in Figs.3(a)-(d) respectively.

It can be deduced from Figs.3(a) and (b) that the overturning moment, induced by the unbalanced liquid pressure distribution and directly related to the tilt angle, must reach a minimum level before any base rim uplift can occur. This minimum level of overturning moment is necessary to overcome the liquid pressure acting on the tank bottom, which resists the tendency to uplift. Fig.3(b) also clearly indicates that the maximum allowable uplift extent of 7% of the radius assumed in the design standards does not seem to correlate with the analysis results.

Studies of seismic tank damage show that many tanks failed because of buckling of the tank shell near the base rim, due to the high concentration of compressive axial membrane stress along the contact portion of the base rim. In Fig.3(c), the compressive membrane stresses are normalized by the tensile membrane hoop stress of a similar but free cylindrical shell subjected to the liquid pressure loading in the initial horizontal position. The shell design provision specified in the design standards is largely based on this reference hoop membrane stress. As shown in the figure, the hoop membrane stress increases more rapidly than the axial stress at the contact point, suggesting that perhaps at large tilt angle, the hoop stress may become an important factor in determining the buckling strength of the tank shell.

Another common seismic failure mode is the tearing or rupture at the bottom plate–tank shell connection. This kind of failure may be initiated by the high bending moment and curvature near the base of the tank shell caused by the restraining action of the bottom plate (Fig.3(d)). It is noted here that the magnitude of the bending stresses at the joint are at least one order of magnitude higher than that of the membrane stresses. Consequently, the effect on the critical buckling load of the tank shell curvature resulting from flexural deformation should also be considered.

Height-to-Radius (Aspect) Ratio

Perhaps the single most important factor affecting the seismic behaviour of an unanchored tank system is its geometry, described by the height-to-radius ratio parameter. From the experience of seismic damage study and shaking table tests, tall tanks typically have a higher tendency to uplift as compare to broad tanks, and thus are more susceptible to seismic damage. The following parameter study seems to agree with this observation. In the present study, the height-to-radius ratio varies from 0.5 to 5, keeping the capacity of the tank and the liquid volume constant. The variations of the same response parameters with the aspect ratio are presented in Figs.4(a)-(d).

As noted in the figures, there is a sudden increase in the uplift response of tanks with height-to-radius ratio between 2 and 3. However, this sudden change in the behaviour does not seem to reflect as significant in the relation between the extent of bottom plate uplift and the aspect ratio shown in Fig.4(b). It is noted in Fig.4(c) there is a corresponding drop in the tank shell membrane stresses on the contact side, possibly due to the combined effects of the lateral displacement and the out-of-round deformation in the tall tank. In comparison, the bending stresses presented in Fig.4(d) increase monotonically with the aspect ratio. In summary, it seems that the height-to-radius ratio of 2 may be conveniently adopted to classify tanks into the two categories of broad and tall tanks, of which tall tanks are more sensitive to lateral acceleration with larger uplift deformations.

Bottom Plate and Tank Shell Thickness

In this parameter study, the tank shell thickness is first kept unchanged, while the bottom plate thickness is modified; then both the tank shell and the bottom plate thickness are varied simultaneously. Because there is no design strength requirement for the bottom plate under the horizontal static condition, but the design standards specify that the bottom plate thickness shall not exceed the bottom shell course thickness, hence the bottom plate thickness is reduced from the standard case of 0.08 in. (2.03 mm) to a smaller value of 0.03 in. (0.76 mm) in order to study the relative contribution to the uplift resistance mechanism derived from the bottom plate. The results are presented in Figs.5(a)-(d).

In both cases, uplift increases as the structure becomes more flexible when the plate thickness is reduced. However, the extent of the bottom plate that uplifted does not change significantly with the reduction in the plate thickness. Similar behaviour is observed for the tank shell axial membrane stress shown in Fig.5(c). On the contrary, the membrane hoop stress increases substantially when a thinner bottom plate is chosen. The results presented in Fig.5(d) seems to indicate that reducing the bottom plate thickness alone tends to decrease the flexural deformation of the tank shell, whereas reducing also the tank shell thickness will have the opposite effect. In summary, a thicker and stiffer bottom plate will reduce the amount of vertical uplift around the base rim, but at the same time will also increase the bending stresses at the bottom plate–tank shell connection, due to the often neglected interaction between the two components.

Stiffening Wind Girder, Bottom Toe Ring and Roof Type

The stiffening effect of the wind girder at the top rim and toe ring around the tank base is studied by varying the stiffness of the two elements in the analysis model.

In summary, the wind girder has the effect of reducing the top rim out-of-round deformation, which is closely related to the warping distortion at the tank base. It should be noted here that the vertical component of the base uplift deformation is essentially similar to the warping distortion of the tank shell. Therefore, a stiffer wind girder increases the overall uplift resistance of the tank system and reduces the amount of uplift. Analytically, a tank roof with rigid diaphragm can be simulated by very stiff wind girder, essentially eliminating the top rim out-of-round deformations.

The only significant effect of increasing the bottom toe ring stiffness is the reduction of the tank shell membrane hoop stress through the reduction of the tank shell out-of-round deformations at the base. As discussed before, this reduction in hoop stress may affect the buckling strength of the tank shell, even though the buckling criterion is often thought to be associated largely with the magnitude of the compressive axial stress.

CONCLUSIONS

The uplift behaviour of unanchored tanks has been investigated in previous studies using the static tilt model. This paper quantifies the sensitivity of the uplift behaviour to some of the important parameters which characterize the tank system. It is found that important aspects of the uplift mechanism have not been adequately considered in the design standards. For instance, the extent of uplift in the bottom plate clearly exceeds the maximum allowable assumed in the design standards even for a moderate tilt angle. It is also found that there is a substantial increase in stresses and displacements associated with uplift when the tank's height-to-radius ratio is increased from 2 to 3. It is also shown the relative thickness of the bottom plate and the tank shell base course has a significant effect on the uplift behaviour. Furthermore, tanks with a rigid roof have greater uplift resistance than open-top tanks with flexible floating roof due to limiting the interaction between the bottom plate and tank shell. Finally, through this parameter study, a better understanding of the uplift behaviour has been achieved, which provides a basis for solving the dynamic uplift problem. A more detailed paper on the parameter study of unanchored tank uplift is currently in preparation.

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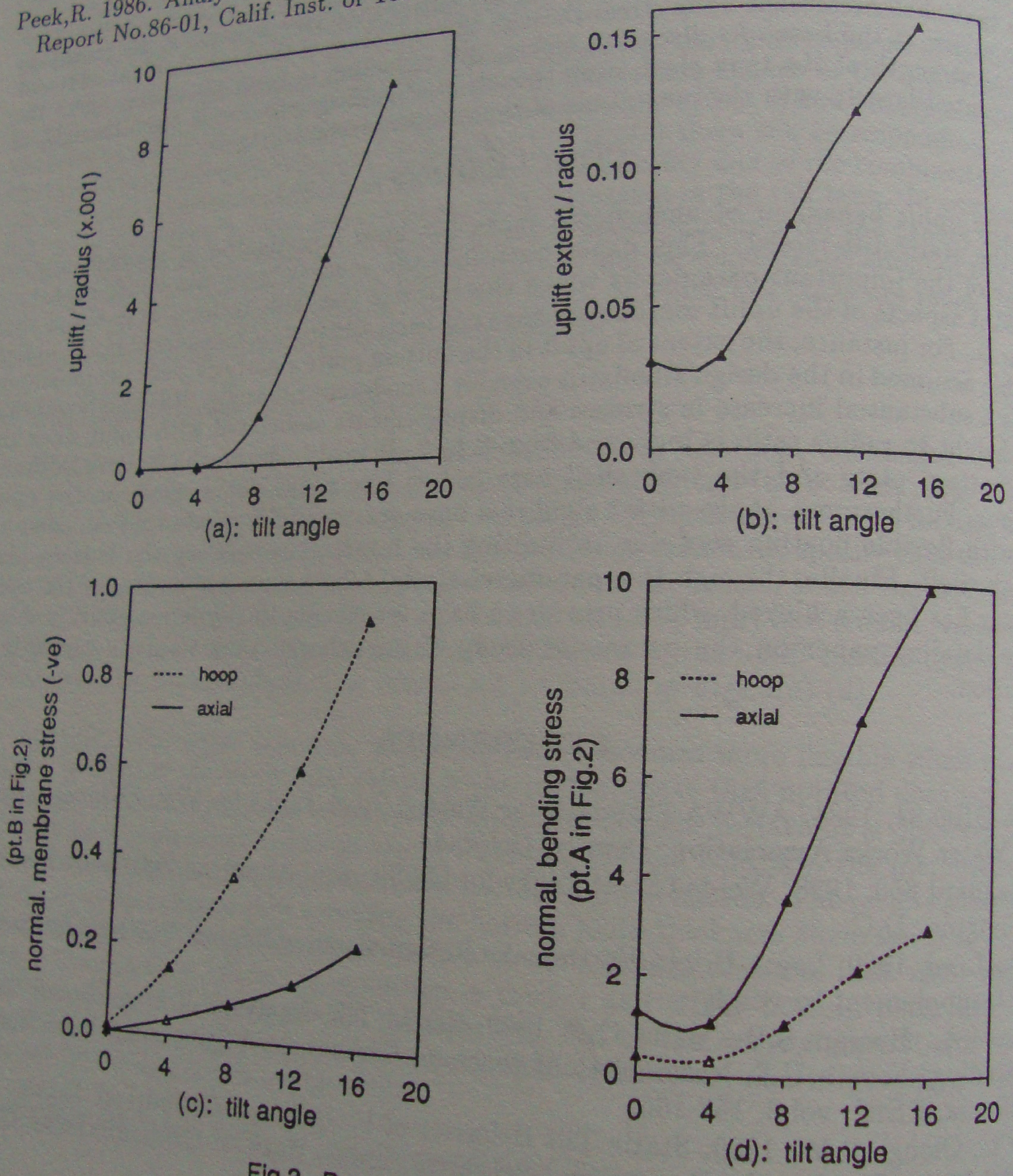

Fig.3. Parameter study of tilt angle

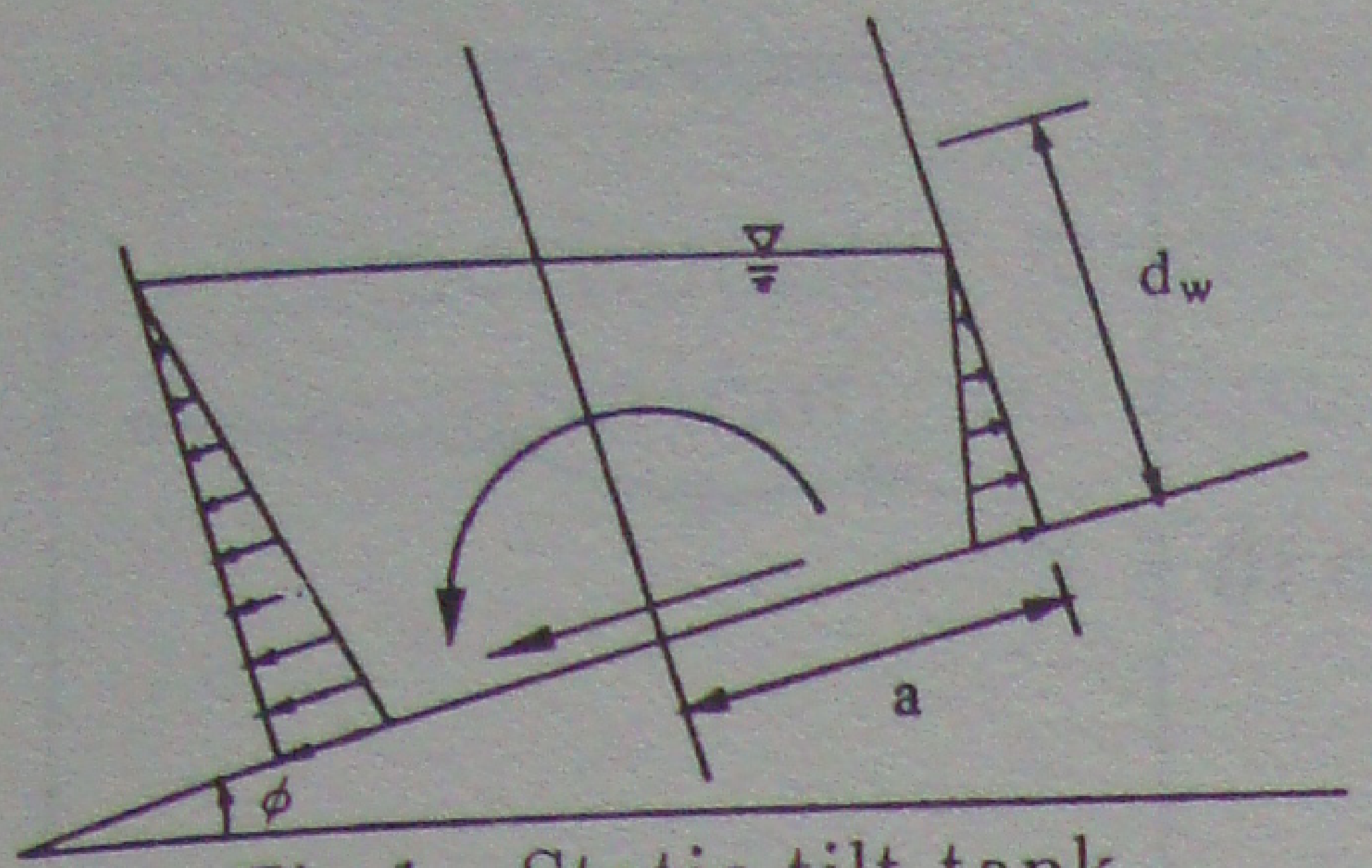

Fig.1. Static tilt tank

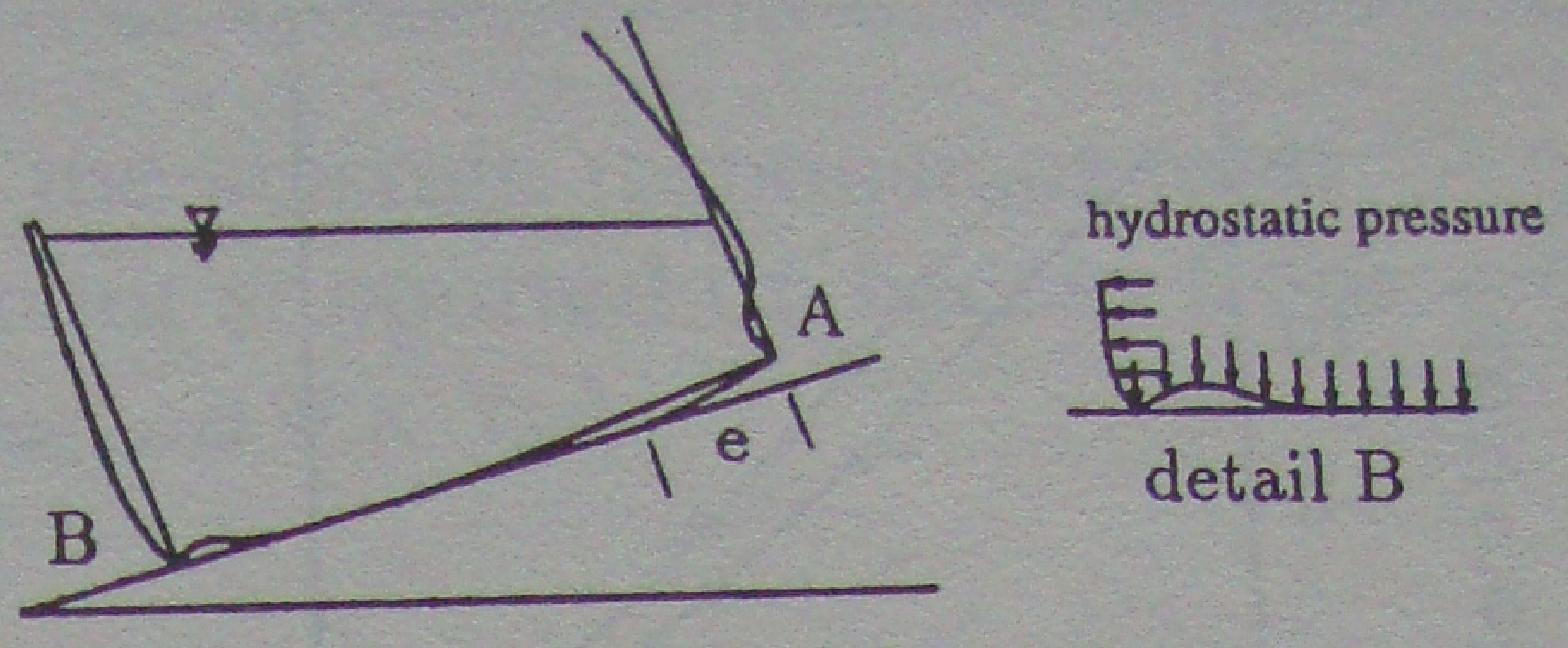

Fig.2. Uplift deformation

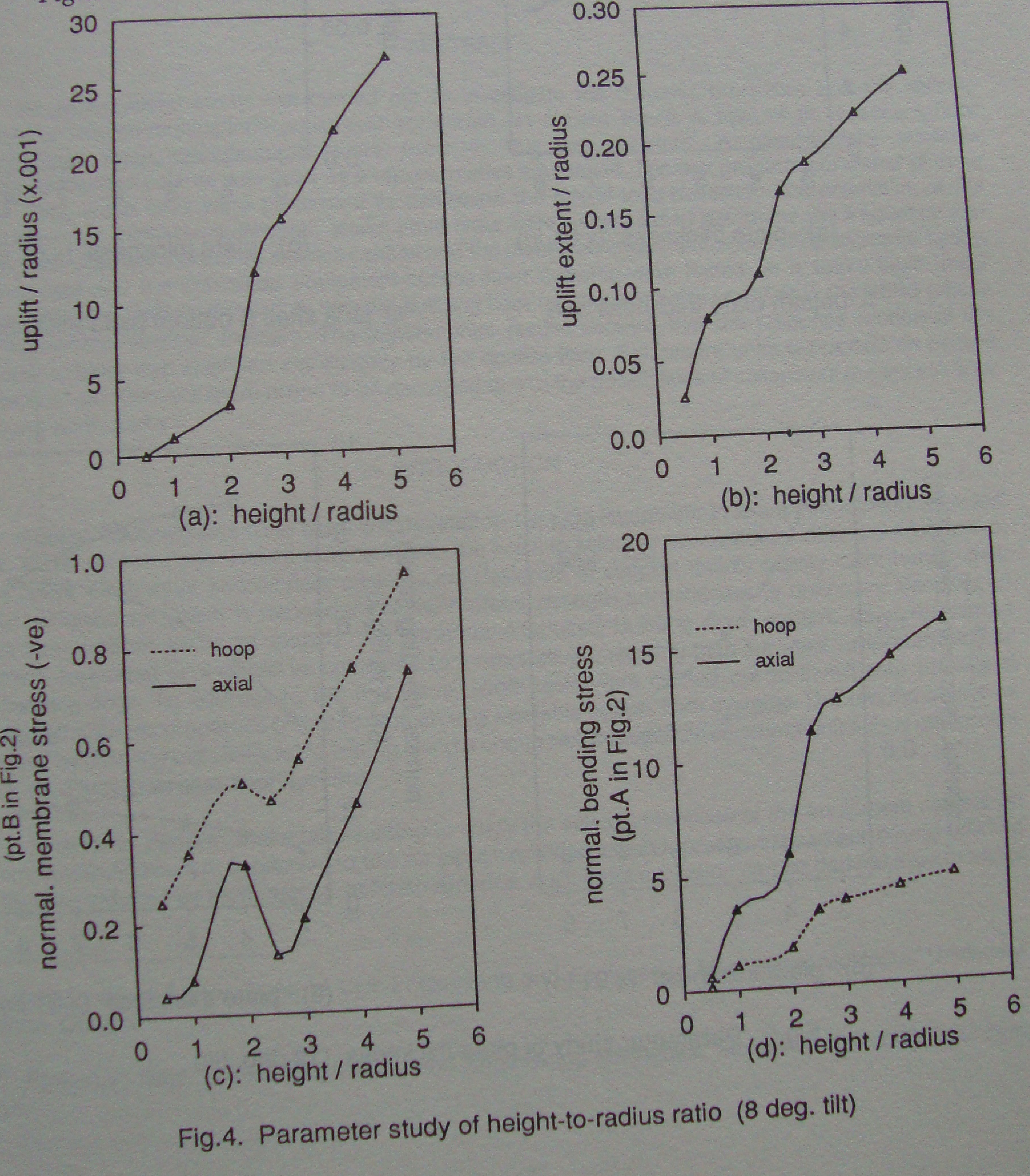

Fig.4. Parameter study of height-to-radius ratio (8 deg. tilt)

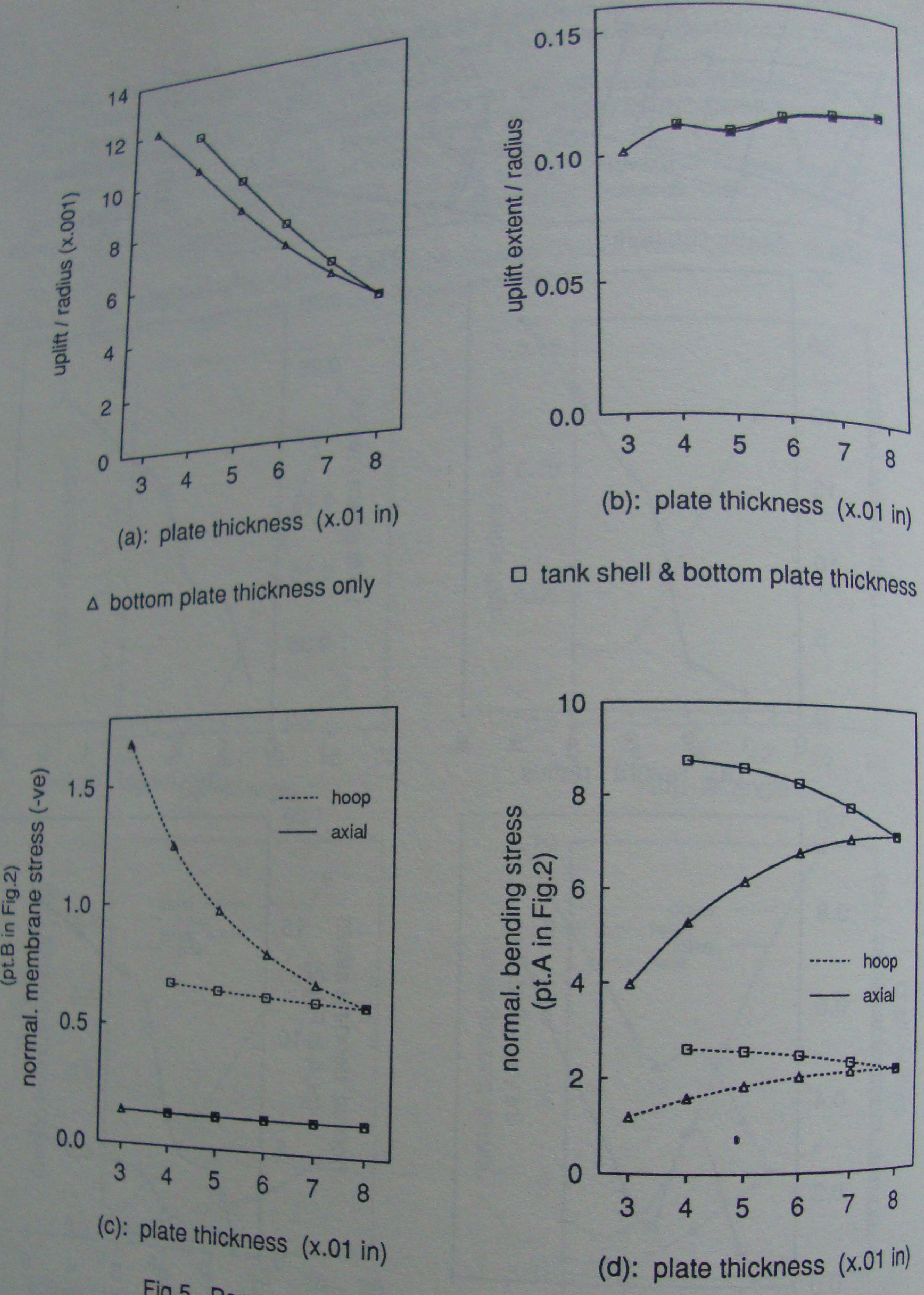

Fig.5. Parameter study of plate thickness (12 deg. tilt)