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ABNORMAL WALL MOVEMENTS OF A STEEL SILO CAUSED BY PADDY RICE STORAGE

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ABSTRACT

The particular rheological behaviour of paddy rice and husked rice, that is readily determined in laboratory using the conventional triaxial apparatus, provided a realistic interpretation of an unusual case history occurred on a large rice storage steel silo. Subsequently it suggested minor modifications, but quite sufficient to ensure the facility availability at different stages of rice storage.

KEYWORDS

Large steel silo - Paddy rice - Rheology of rice - Structural stability - Silo with internal ties.

INTRODUCTION

In the last decades, a huge number of large metal silos have been built, as the mining, materials handling, and process industries have grown and changed their methods in bulk solids handling. As a result of the high failure rate in silo structures, great effort had been spent for better understanding of silo pressures and flowing phenomena [Kühnemund 1987].

Steel silos differ markedly from concrete silos. They are thin shell structures. A thin shell is the most structural efficient form, but consequently it is also the most sensitive to variations from the conditions for which it represents an optimum. A metal silo is much lighter than its concrete equivalent. It is easy to fabricate in a factory setting, and quick to erect. It carries the loads by membrane action, deforming readily and reversibly when subject to unsymmetrical loads, and placing smaller loads on its foundation. The aspect ratio of many of these metal silos is much squatter than the conventional slender concrete silo so widely studied in the silo pressure literature. Thus different issues for structural strength arise [Borcz 1987, Carson and Jenkyn 1993].

Metal silo storage of bulk solid materials generates an unusual class of both structural and functional failure problems, mainly caused by a misunderstanding of the rheology of the great variety of stored products [Carr 1965, Blight 1986]. The knowledge of their mechanical behaviour permits a better evaluation of loads and stresses acting on the silo walls.

Available methods for analysing of silos give results that vary a wide range even under static conditions. They are not generally on the safe side. Due to the underlying assumptions and their incompleteness, most approaches are restricted to the analysis of simple geometry and static or at rest conditions only. Furthermore inertia effects [Levison and Munch-Andersen 1993] are neglected. Elastic-plastic, viscoplastic models [Häussler and Eibl 1984] or more sophisticated constitutive models are used for the bulk material. As will be shown later on, this idealisation may be incorrect and leads to major errors. The aim of the present paper is to illustrate the relevant use of conventional triaxial tests for a better understanding of both the mechanical behaviour and flow properties.

Fig. 1 A 100,000 t capacity rice storage complex.
DESCRIPTION OF THE STORAGE COMPLEX

A large paddy rice storage complex of steel silos comprises 10 square cells of 12.50 m x 12.50 m x 16.00 m in size, offering a capacity of 100,000 tonnes (Fig. 1). The vertical walls are stabilised with internal ties according to regulations and standards [Afnor 1991]. They are constituted of steel rods of 32 mm in diameter (Fig. 2), capable to withstand the active pressure of stored materials.

STRUCTURAL SURVEY

Abnormal inward wall movements (Fig. 3) occurred during the first successive filling and emptying operations of paddy rice in the different square cells of the storage complex of steel silos. Some connections between internal ties and vertical walls have failed (Fig. 4), threatening the overall stability of the infrastructure of the storage complex. It results a reduction of storage capacity leading to loss of profitability. There is then a need for a comprehensive interpretation of this structural problem before finding the appropriate techniques for repair and improvement.
Fig. 5 Measured deflections on silo cells No. 4 and 6.

Measured deflections (Fig. 5) of silo walls during filling operations demonstrated the influence of the rheological behaviour of paddy rice.

Examinations of the steel silo (Fig. 6) has been made after the first occurrence of abnormal wall movements.

TRIAXIAL TESTING ON PADDY RICE

In order to evaluate loads and stresses on the silo walls, it has been decided to use conventional triaxial tests, well known in soil mechanics, for the analysis of the mechanical behaviour and flow properties of paddy rice.

The particular rheological behaviour of a paddy rice (Fig. 7) has been readily determined in laboratory using the conventional triaxial apparatus.

Series of triaxial tests on paddy rice were conducted on cylindrical specimens 70 mm in diameter and 160 mm high. For each test, stress-strain curves recorded during loading give the volume change $\Delta V$ referred to the initial volume $V_0$ and the axial displacement $\Delta h$ with respect to the initial height $h_0$ as a function of the axial force $\Delta F$ referred to the initial section $S_0$ of the specimen (Fig. 8).

The pseudo Poisson coefficient, defined by the ratio $\text{measured horizontal strain} / \text{measured vertical strain}$, shows very low values at low confining pressures. This fact is due to the deformability of constituent particles. Very low active pressure will act on the silo vertical walls during storage operations of paddy rice.

Stored paddy rice will load uniformly on the internal ties acting as flexible steel rods. They thus behave as hammocks subject to uniform loads (Fig. 9) pulling on their hinges and tend to reduce the span, leading to abnormal inward movements of silo walls.

To prevent from inward movements of silo walls, internal ties must form a rigid frame with the columns (Fig. 10), minimising column moments.
Repair suggestions readily propose replacement of all flexible steel rods by stiff internal ties in order to apply loads downward, directly on the columns. Experimental results thus provided a realistic and convincing interpretation of this unusual case history occurred on a large steel silo for paddy rice storage with internal ties. They subsequently permit ready repair decisions.

METHOD OF REPAIR

Normal pressures, acting on the walls of a silo storing paddy rice, husked rice, wheat and other foodstuffs, may vary with the method of filling, rate of filling, stiffness of the silo walls, variation in flow properties of the bulk solid, silo wall imperfections, segregation while filling, rate of de-aeration, material temperature changes, and an increase in grain moisture causing swelling.

Conventional methods of pressure evaluation on silo walls are based on theories of arching, allowing the transfer of pressure from a yielding mass of stored material on to adjoining stationary parts. Most of the theories of arching deal with the pressure of dry material on yielding horizontal strip.

i. Some workers considered the condition for the equilibrium of the material which is located immediately above the loaded strip without attempting to investigate whether or not the results of the computations are compatible with the conditions for the equilibrium of the material at greater distance from the strip [Janssen 1895].

ii. Other workers assumed without realistic justification that the entire mass of the stored material located above the yielding strip is in a plastic equilibrium [Caquot 1934].
A third group assumed that the vertical sections through the outer edges of the yielding strip represent surfaces of sliding and that the pressure on the yielding strip is equal to the difference between the weight of the material located above the strip and the full frictional resistance along the vertical sections. The real surfaces of sliding are curved and at the surface of the material their spacing is considerably greater than the width of the yielding strip. Hence the friction along the vertical sections cannot be fully active. The error due to ignoring this fact is on the unsafe side.

Hence the conventional methods for determining the stress fields in silos are generally based on the limit equilibrium equations of a two-dimensional rigid plastic continuum, a failure condition that does not take into account deformation characteristics and the mass flow type of stored materials when emptying.

Using traditional notions of Rankine active and passive pressures, several workers have attempted to evaluate debatable stress distribution on the silo walls without taking into account realistic boundary conditions. Obtained solutions are statically and plastically admissible. They correspond to lower bound values.

Experimentally, a large number of studies carried out in France [Brozzetti 1989] and elsewhere showed that wall pressures varied with time, and that outlet operations with a small quantity of material changed the load values in a very significant manner.

This is also the case during the process of silo handling in filling and emptying. The applied loads on silo walls are a function of the shape, the bottom, the type of flow during emptying and the outlet location. The load distribution varies significantly with the nature of stored materials: compressible types such as foodstuffs, abounding types such as pulverised coal, cement, gypsum and limestone, or dilatant types such as hard angular grain mine products.

These experimental observations indicate the predominant influence of the rheological behaviour of bulk solid materials to be stored [Luong 1989] on the determination of loads to be considered in silo design.

Three types of constitutive models have been used to describe granular flow in various geometries:
- kinetic models [Jenike 1964],
- rate-independent or frictional models based on plasticity theory and soil mechanics [Schield 1955, Mandl and Fernandez-Luque 1970], and
- rate-dependent or collision models based on the kinetic theory of gases.

It is noted that none of them is wholly satisfactory or even superior to the others in all respect. Kinetic models are incomplete because they provide no information about stress field and density variations. Nevertheless they have been reasonably successful in predicting velocity profiles in the converging flow zone of flat-bottomed bins. Frictional models have been in use for over two decades.

The results of these studies show that the models can predict some, but not all, of the mechanical phenomena observed when granular materials flow through hoppers and bunkers [Teng and Rotter 1991].

Collision models have been explored largely from the 1970 onwards. They have predicted some features of plane shear between parallel plates and some characteristics of flow down inclined planes.

Recently hybrid frictional-collision models have been developed and applied to these problems, with encouraging results [Goodman and Cowin 1971].

The particular rheological behaviour of paddy rice, readily determined in laboratory using the conventional triaxial apparatus [Luong 1978, 1993], suggested that the role of active pressure caused by the Poisson coefficient effects (Fig. 11) may be negligible and overburden loads predominantly pull on the flexible internal ties.

**STRUCTURAL REDESIGN**

Subsequently it was decided to remove all the flexible steel rods acting as internal ties and to replace them by steel tubes having the same material cross section and therefore presenting a higher beam stiffness (Fig. 12).
CONCLUDING REMARKS

The particular rheological behaviour of a paddy rice has been readily determined in laboratory using the conventional triaxial apparatus. When active pressures, generated by the stored products, are low, stiff internal ties are required to ensure the stability of the structure. Experimental results allowed a realistic and convincing interpretation of an unusual case history occurred on a large steel silo for paddy rice storage with internal ties.

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