Advanced Powder Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Advanced Powder Technology

journal homepage: www.elsevier.com/locate/apt

Original Research Paper

Silo quaking of iron ore train load out bin – A time-varying mass structural dynamic problem

Phung Tu *, Vanissorn Vimonsatit

School of Civil and Mechanical Engineering, Curtin University, Perth, Western Australia, Australia

ARTICLE INFO

Article history:
Received 1 April 2017
Received in revised form 11 September 2017
Accepted 15 September 2017
Available online xxxx

Keywords:
Silo quaking
Time-varying mass structural dynamics
Train Load Out Bin

ABSTRACT

Expanded flow bins are commonly used in the material handling industry to store and load train wagons. These bins are known in the industry as Train Load Out (TLO) bins. Several iron ore TLO bins have been designed and constructed to accommodate this demand. It has been reported that some iron ore TLO bins suffer a dynamic condition during discharge known as silo quaking. The quake causes several problems, which could lead to structural connections failure, reduced fatigue life of structural connections, computer data corruption, on-site personnel discomfort, loss of production, and increase in maintenance costs. However, the author had structurally designed a 2500 tonne iron ore TLO and prevented silo quaking by providing sufficient stiffness, damping and mass to counterbalance the pulsating loads and mass losses produced by the flowing iron ore. In this paper, a numerical model incorporating time-varying mass will be presented to explain the dynamics of Iron Ore TLO Bin. The model is validated by experimental results obtained from a 1 in 10 scaled model. The proposed numerical model supports the theory that pulsation loads occur in almost all bins and whether the induced dynamic loads cause any quaking problems are dependent on the severity of the loads, natural frequencies of the bin and its supporting structure.

1. Introduction

A typical process diagram for an iron ore mine is shown in Fig. 1. As seen in the diagram, iron ore boulders are transported from a mine pit to the Primary Crusher building where they are crushed into smaller lumps of 30 mm and fines of 6 mm in size. The lumps and fines are then transported by a belt conveyor system to the Product Screening building where the crushed ore is separated into lumps and fines. Any lumps bigger than 30 mm are transported to the Secondary Crushing building where the oversize ore is crushed into smaller fragments and transported back to the Product Screening building. After that, the lumps are transported by conveyor to the Lump Stacker, and the fines are transported to the Fine Stacker at the stockyard. The stackers fill the lumps and the fines stockpiles which can be reclaimed as required by the Reclaimer. The Reclaimer fills the belt conveyor which then fills the Train Load Out (TLO) Bin. The TLO Bin has a clam shell gate at the bottom of the hopper which can be opened up to discharge the ore into the train wagon as it passes slowly underneath the TLO Bin.

The inclusion of a TLO Bin in the Mine Process has proven to be a more efficient way for loading the train wagons, and it is also more cost effective when compared to the traditional Train Load Out Vault and Stockpile. These iron ore TLO Bins quite often have a storage capacity of 2000 tonnes. In recent years, iron ore TLO Bins have been designed to have a storage capacity of 2500 tonnes. TLO bins often are designed using expanded flow regime. Expanded flow is a bulk solid flow regime where the ore at the upper portion of the bin is designed for funnel flow, and the lower portion of the bin is designed for mass flow. The advantage of the expanded flow regime is the ability to store a large amount of ore in a squat bin while still maintaining mass flow without the need for a much taller bin. Roberts [1] suggested that tall bins require conveying the ore to the top of the bin where the filling process occurred impractical at mine sites. These TLO bins are often made from structural steel and are circular in shape rather than square or rectangular. Square or rectangular bins carry the pressure loads of the stored iron ore on the bin walls in bending and shear stresses whereas circular bins carry such loads in hoop stress. Consequently, large TLO bins that utilise hoop stresses to carry the pressure loads acting on the walls will require less steel compared to square or rectangular bins. However, there have been some reports from various mine sites that these iron ore TLO bins suffer excessive vibrations during

* Corresponding author.
E-mail address: phung.tu@postgrad.curtin.edu.au (P. Tu).

https://doi.org/10.1016/j.apt.2017.09.012
0921-8831/

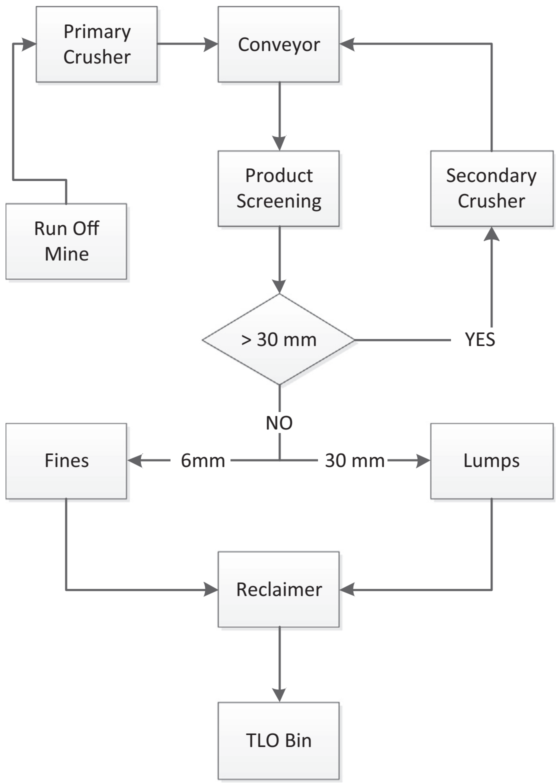

Fig. 1. Typical iron ore mine process diagram.

ore discharge [2,3]. The first author had structurally designed a 2500 tonnes iron ore Train Load Out silo in 2008 and successfully avoided the silo quaking phenomena by changing the structural stiffness, damping and mass of the supporting structure and foundation [4]. It was pointed out that silo vibration spectra are similar to that of earthquake spectra and there are discreet zones within the silo vibration spectra where the fundamental natural frequencies of TLO bins could be set to minimise the effect of silo quake. Therefore, dynamic properties and behaviour of TLO bin and its supporting structure need to be investigated.

The vibration starts as soon as the clam shell gate at the bottom of the TLO bin opens to discharge the ore into the wagon passing underneath it. The motion quickly intensifies and dissipates as the clam shell gate closes and the motion repeats itself as the clam shell gate opens to load another wagon passing under. These types of vibration are commonly described in the research literature as Silo Quaking.

The quaking causes several problems, which could lead to structural connections failure, reduced fatigue life of structural connections, computer data corruption, on-site personnel discomfort and health related issues, loss of production, increase in maintenance costs and catastrophic failure as noted by Chou, Chuang, Smid, Hsiau and Kuo [5]. Thus effectively making Silo Quaking an industry problem that has occurred ever since the first silo was built.

It is believed that pulsation loads occur in most bins, whether the induced pulsating loads cause silo quake depends on the severity of the load, natural frequencies of the bin and its supporting structure [6]. Furthermore, Kmita [7] identified the silo quaking phenomena as a system of self-induced vibration.

Researches to date have focused heavily on estimating the pulsating loads generated by the silos during discharge. Although the field of structural dynamics has advanced significantly over the last few decades. To the authors' knowledge the dynamic structural characteristics of the silo structure have not previously been studied in detail. Evidently, there is not any detailed guidance given in any international design guides on dynamic analysis of silo structure to prevent silo quaking.

Let's consider a silo structure as a structure consisting of both stationary masses such as self-weight of the silo and its supporting beams, columns, braces and foundation and the temporary mass of the granular material stored in the silo. During discharge, the total mass of the silo structure including the stored granular material reduces with respect to time. Therefore, the dynamics of the silo structure as a whole also change with respect to time. The current structural dynamic formulations do not take into consideration the time varying mass characteristics of the silo structure during discharge thus requiring modifications for analysing such structures.

It will be demonstrated in this paper that silo quaking is a natural process where the silo structure restores its state of equilibrium because its state of equilibrium was disturbed by the pulsating loads and mass losses. This equilibrium restoring process can be readily observed for most things that exist in nature.

A review of the current structural dynamics analysis methods and an equation incorporating principles of time varying mass structural dynamics to prevent the silo quaking phenomena will be presented to demonstrate that silo quaking is the process used by the silo structure to maintains its dynamic equilibrium because its dynamic equilibrium has been disturbed by the pulsating forces and mass losses. The proposed equation does not exclude the pulsating loads generated by the silo during discharge as theorised by other researchers but rather incorporates them with the fundamentals of time varying mass structural dynamics to explain the silo quaking phenomenon and most importantly provide a theoretical framework for structural engineers to prevent silo quaking by providing sufficient stiffness, mass and damping in the silo supporting structure. The equation also illustrates that the mass losses alone can cause the silo supporting structure to sway because the silo supporting structure needs to restore its equilibrium which has been disturbed by the mass losses. Thus the proposed equation is called the equation of silo quaking. The equation of silo quaking is validated by experimental data taken from a 1 to 10 scale of an industrial Train Load Out (TLO) silo containing iron ore.

The method of preventing silo quaking in TLO by implementing principles of structural dynamics has been implemented successfully in practice. Furthermore, principles of structural dynamics are often sourced by structural engineers to modify the silo support structure to reduce the amplitudes of vibration caused by the flowing granular materials. The TLO has been in operation since 2010 without quaking issues. Based on the successful implementation of the method of providing extra stiffness, damping and mass in the silo support structure to prevent silo quaking without referring to any existing literature on silo quaking indicate the shortcomings present in the current literature on silo quaking thus forming the basis of this paper.

It is recommended that the reader familiarise themselves with the concepts of time varying mass structural dynamics and transient structural dynamic analysis because such concepts are implemented in this paper to prevent the silo quaking phenomenon. Time varying mass structural dynamics typically belong to the field of rocket science. Thus literature can be found on National Aeronautics and Space Administration (NASA) website or similar.

2. A review of the dynamic response analysis methods

The advance of modern computers has allowed the practising engineers the ability to implement numerical methods formulated to predict the response of the structure due to dynamic loadings. As described by Hart and Wong [8], the stiffness matrix method