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Research Article

NEW APPROACHES IN MATHEMATICAL MODELING OF GRAIN STORAGE

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Abstract: The mathematical modelling in grain storage structures is very old. There are two types of modeling are suggested in grain storage structures- Numerical models and Analytical models with/without parametric assessment. The Analytical mathematical models in grain storage structures are very primitive and widely used approach in grain storage. Analytical models' use of Rankine earth pressure theory in grain storage like bin or silo design, Airys stress determination in grain storage structures, use of Janssen's (1895) equation in silo design are widely used common approaches in bin design. Analytical design methods of Silo design use necessary material parameters such as bulk density, coefficient of friction on the wall and pressure ratio allows for calculation of wall and floor loads with acceptable accuracy. The Numerical methods approaches for grain storage structures includes Computational Fluid Dynamics for grain environment modeling in standardizing the grain health and minimization of post-harvest losses this includes the pest loss, rotting of grain due to excessive humidity and temperature. In Numerical Method approach is Finite Element Methods this helps in designing the structures and components design of grain storage structures.

Keywords: *Numerical Models, Analytical Models, Mathematical Models, Bin and Silo design, Grain Storage*

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Introduction

Normally silo/bin was used to store grains; this silo design was based on earth pressure theories of active and passive pressure based on Rankine theory [1]. Later on, Janssen's (1895) [2] gives an acceptable and widely used silo design based on granular materials which suitably assume the vertical and horizontal pressure inside the silo for grain storage. This Janssen's theory used the exponential function of the depth of the grain in silo/bin [Eq-1].

$$\sigma_z = \frac{\rho g D\left(1-e^{\frac{4k\mu z}{D}}\right)}{4k\mu} \qquad (1)$$

$$\sigma_x = k\sigma_z$$

Where:

D = silo diameter (m); g = acceleration due to gravity (9.81 m/s^2); k= horizontal to vertical pressure ratio inside the silo/bin; z= depth of grain inside the silo/bin; μ coefficient of wall friction of the silo/bin; ρ bulk density in kg/m^3; σ_x horizontal pressure in Pa, σ_z Vertical pressure in Pa; μ coefficient of friction grain to grain contact in of the silo/bin;.

Silo design didn't stopped here they introduced the Airy's stress mechanism inside the silo to explain the flow of stresses inside the silo due to grain [3]. It is explained in the equation given as under taken from IARI [4] research [Eq-2]. This Airy's stress function modified to accommodate the grain-to-grain interaction inside the silo/bin.

$$\sigma_x = \rho z\left[\frac{1}{\sqrt{\mu'(\mu'+\mu)}+\sqrt{1+\mu'^2}}\right]^2 \qquad (2)$$

Grain storage structures are built in Northern India particularly Haryana, Punjab, National Capital Region Delhi and Uttar Pradesh. They are mostly steel silo/bins of very low cost. Large structures related to grain storage rests with the government godowns (large rooms with pairing along line or in square form made of wood logs). In these godowns gunny bags of grains are piled up on the wood logs or manufactured ply boards. The only mechanisms of aeration are spacing between wood logs and ceiling between roof and top of gunny bag heap.

Hence forth identification of storage processes are must and their mechanization will be sequentially carried out along the construction of storage structures. Here in [Table-1] mentioned list identified the before and during processes of grains in storage and few of the traditional storage structures of India are listed in [Table-1] [5]. The main objectives of the grain storage structures must be outlined before starting designing, fabrication and construction of structures. Few of the purposes of the grain storage structures are mentioned in [Table-1].

New Factors Influencing the Mathematical Modeling of Silo/Bins

Dynamic friction coefficient of cereals and other agricultural crops is required to design silos, agricultural crops storage structures, transporting devices such as belt conveyor and screw conveyors, and it also affects the performance of postharvest equipments [6]. Dynamic friction coefficient is influenced by many factors such as product/grain variety, grain moisture content, grain to grain contact & silo/bin wall contact surface and sliding velocity. Chung *et al*., (1984) [7] describes that material contact surfaces affects more on the dynamic friction coefficient than the static friction coefficient. The Dynamic coefficient increased with the increase of sliding velocity at all moisture content levels of grains concluded by Kappuswamy and Wratten (1970) [8]. At higher moisture content, as grains was sticky in nature, adhesive force played an important role in increasing the value of the dynamic friction coefficient. The dynamic friction coefficient mean significantly increased while by increasing the sliding speed.

As part of new approaches instead of static friction coefficient, dynamic friction coefficient gives advantages over the controlling mechanism of temperature and moisture in the grain storage. It is because dynamic friction coefficients have relationships with temperature and moisture content of the grains. Whereas static friction coefficients have lesser correspondence with temperature and moisture of the grains [9]. Humidity inside the storage and moisture levels of the grains has serious relationships inside the silo/bin. This will effect pest infestation, dry and wet rotting of grains inside grain storage.

Table-1 Typical Types of Grain Storage Structures in India and Associated Processes

SN	Various types of traditional grain storage in Haryana	Types of processes required before entering grain in structure	Objectives of Grain Storage
1	Jute bags	Threshing	Quantity of grains
2	Bukhari	Winnowing	Purpose(commercial/household/seed)
3	Parchhattu	Cleaning	Time period
4	Heap in room	Drying	Place of storage
5	Metal bin	Storage	Treatment like fumigation or disinfections
6	Metal containers	Peat control methods	Frequency (iterations from the bin/silos)
7	Plastic bags	Bagging	Frequency of the Treatment
8		Ponding	Control measures and readiness like dampness, humidity, temperature *etc.*
9		Dehusking	Quality of the grain
10		Decortication	Modern measures if any application like osmosis, salt, sugar, oil, sun drying.

Table-2 Available Technologies in Numerical Modeling of Grain Storage Structures

SN	Technology available to agriculture in India	Probable use of technology	Intervention of technology
1	Matlab*, Scilab*, Mathworks*, ANN, any statistical approach.	Numerical calculation	Programming
2	Finite Element Method	For simulation of boundary conditions of the system	Abaqus*, ANSYS* *etc.*
3	Computational Fluid Dynamics	For simulation of flow conditions of the system	ANSYS* primarily
4	Computer Aided Design	For fabrication of component	AutoCAD*
5	Structural Designing	In case of bin/silo	ETAB* for metal bin, STAAD* for concrete bin

This high humid climatic condition is not suitable for grain storage. Due to very high relative humidity (70% to 98%), it is difficult to preserve the quality of the grains inside the silo/bin. By controlling the moisture and air movements in the silo/bin helps in preventing attack of microorganisms, insects and rodents [10]. The storage of grains at low temperature (10 to 15°C) and maintained seed moisture at a favorable level (10%) ensuring its germination potential at a high level for a considerable period (270 days) inside the silo/bin.

Temperature and moisture content were higher in the soil pits and indigenous grain storage structures than in the bins, cements and dung pits. The silo/bins maintained the lowest temperature and grain moisture content. Bulk density of the stored grains from the soil pits/ borrows were decreased by upto 9%, while the changes in bulk density of the stored grains in the other storage methods were not significant. These details given above are inspired from the research work of Horabik and Molenda (2002) [11].

Numerical Methods/Modeling Approach in Grain Storage Design

Traditional methods have very limited future in Indian rural villages widespread post harvest losses were reported in traditional grain storage structures. Poor quality of the stored grains due to pest infestation, high humidity levels, increased germination potential only add to the existing trouble of spectacle temperatures with spatial-temperate climates. This requires new verified approaches to control the environment of silo/bin and storage structures. Analytical methods have limitations pertaining to constructional material behaviour which is normally metal bin or concrete/brick silo. Two methods coupled together with elemental methods/mechanics and fluid dynamics giving the solutions to modern storage structures. The available numerical methods and approaches are explained in [Table-3] and all these technologies have commonality in terms of numerical calculation and designing steps as described.

The typical flow chart was followed given in Shrestha *et al.* (2016) [12] it originally belongs to Dieter *et al.* (2000) [13] for Numerical and analytical approaches. However Finite element methods approaches for grain storage structure are very in early stage in India. However, two notable publications worth mentioning in implementing the Finite element method approaches for Indian grain storage systems are Puri and Manbeck (1991) [14] and Subash *et al.* (1991) [15].

Analytical Methods/Modeling Approach in Grain Storage Design

As described in the table, mentioned analytical models are very successful in designing load calculation for bins/silos. This [Table-3] analytical model coupled together with local available standards in Indian Standard Codes gives the suitable design for storage structures. The analytical design methodologies for silo and bins are standardized in various codes like ASAE EP433 [16], ACI 313, ACI313-97/313R-97, German Code, DIN 1055 [17], European Code [18], ENV1991-4, Australian Code [19], AS 3774. However, these standards are easily implemented through numerical approaches given in [Table-3]. However wherever computing facility are not available these code provisions are easily get implemented through spread/excel sheets.

Table-3 Analytical Modeling of Grain Storage Structures

SN	Standard Theory and associated name
1	Earth Pressure theory [2]
2	Elastic theory and Airys Stress [3]
3	Earth Pressure and Reimbert Analysis [20]
4	Limit State Design for Concrete Silo/Bin [21]
5	Rankine's Methods [22]
5	Limit State Design for Steel Silo/Bin [23]
6	Composite Material Design approach [24]
7	On field storage (Cover and plinth area, CAP) and Polybags storage (Hermatic storage) [25]
8	Underground Storage (in built caves)

Closed form solutions

In this analytical approach idealization with suitable assumptions according to standard theory of elasticity and plasticity carried out. According to the review of the author, following theory widely used in the designing of silo/bins and governing equations are modified according to crop produce, processes techniues, construction material and agro-metrology parameters of the post harvest produce.

Iterative methods

These methods are based on standard numerical methods based on regression and correlation, Descriptive statistics and statistical techniques and higher order differential equations. These parameters may be evolved in the field experiments and trials of agriculturist or based on closed form solutions.

Spread/Excel sheets

This approach is a mix of closed form solutions and Iterative methods. In which we use the spread sheets and excel sheets for row and column wise calculations based on identified design parameters. And designing will be carried out final submitted or summarized calculations of design parameters.

Design examples in India

The classical examples from these new mathematical approaches were given in Shrestha *et al.* (2016). This is designing and fabrication of winnowing machine for rice paddy in Nepal. This machine modeling was carried out in FEM and CFD code this gives the separation of rice and husk.

Conclusion

The new approaches identified in numerical methods provide better controls on the grain storage systems; this has been demonstrated in the field trials and laboratory studies.

Use of instrumentation viz. sensors, humidity meter, Aeration fans and air conditioning sharpen the edge against post harvest loss.

Application of research: Study of designing of bins/silos for grain storage structures and to fulfil the need of grain storage handling equipment.

Research Category: Agricultural Engineering and Technology

Abbreviations: D = silo diameter (m);
g = acceleration due to gravity (9.81 m/s^2);
k= horizontal to vertical pressure ratio inside the silo/bin;
z= depth of grain inside the silo/bin;
μ =Coefficient of wall friction of the silo/bin;
ρ =Bulk density in kg/m^3;
σ_x =Horizontal pressure in Pa;
σ_z =Vertical pressure in Pa;
μ =Coefficient of friction grain to grain contact in of the silo/bin.

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