Bulk solids stacking strategy of a rectangular ship cabin

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Article

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Abstract

Bulk solids stacking in terminals, ships, trains and other bulk solids storage yards is always challenging considering the requirements of the optimal utilization of the storage area. In this study, the stacking shapes of a variety of bulk solids with different particle sizes were tested, and the curved shapes of the stockpiles were extracted to establish the actual three-dimensional models of the bulk solids accordingly. The three-dimensional curved stockpiles were used to design the bulk solids stacking strategy where the bulk stacking locations, the stacking volume and the flatness of stacking were optimized. A modified golden section method with a self-influenced factor was developed to improve the calculation efficiency of the stacking algorithm for bulk solids stacking flatness. Furthermore, the bulk solids stacking strategy and algorithm were verified by experiments. The results showed that the curved three-dimensional models were very close to the actual shapes of the bulk solids stockpiles while the improved golden section method was more accurate and efficient than the traditional golden section method in finding the optimal values of the stacking volumes for flatness. For different bulk solids tested, the experiment results showed that good flat stacking can be achieved by the developed stacking strategy.

1. Introduction

With the rapid development of bulk solids markets, the storage and transportation of coal, ore, grain and other bulk solids are widely used in diverse industries. The reasonable stacking of bulk solids in a port yard and the balanced and stable loading into bulk solids transportation equipment such as ships and trains are particularly important. At present, the automation of bulk solids stacking is low. It is difficult to reasonably plan the locations and volume in the stacking process. As a result, the positions of stackers for stacking bulk solids in a storage yard are manually adjusted, which frequently causes uneven distribution of bulk solids and uneven stacking effect. Therefore, it is extremely important to reasonably design the stacking and loading strategy of bulk solids to achieve the effect of flat stacking.

In order to realize the flat stacking of bulk solids, it is necessary to establish a strategy that can predict the shape, volume and location of each bulk solids stockpile in a storage yard. Angelelli et al. studied the scheduling problem of stacker reclaimer in the stockyard of a coal export terminal. They introduced an abstract model of stacker reclaimer scheduling and studied the complexity of different variants of the model as well as algorithms for the solution of these variants. A critical assumption in this investigation is that all stockpiles to be reclaimed can and have to be placed on the two pads before reclaiming starts. On this basis, Kalinowski et al. studied a variant of the stacker reclaimer scheduling problem in which this restriction is removed and, as a consequence, stockpile placement and reclaiming sequencing and routing decisions become more involved. Ünsal studied the complex parallel scheduling problem of stacker reclaimer in bulk cargo terminal, and proposed a new constrained programming formula to solve this problem, which can generate near optimal scheduling for different yard configurations in one minute. Pang and Su developed a king view-based bulk solids loading and unloading monitoring system to provide real-time feedback of the stacking process with unmanned remote control. Xue used the laser
scanner installed on the bulk solids ship loader to scan the three-dimensional contour of the cabin and
the materials in the cabin. The shape of the materials in the cabin was obtained using an image
processing algorithm, from which the free space was calculated and filled to achieve flat stacking. Sun et
al.\(^6\) considered the storage space allocation problem motivated by an inland bulk material stockyard and
addressed various practical concerns of the storage space allocation in bulk material stockyard. A novel
mathematical formulation was developed based on the idea of partitioning the storage space into slots.

To sum up, the research of bulk solids stacking mainly focuses on the scheduling of bulk solids stacking
equipment, the intelligent monitoring of stacking site, the detection and feedback of stacking effect and
the rational utilization of yard space. However, there is little research on the strategy planning of flat
stacking of bulk solids. The distribution of bulk solids in stacking process still needs manual intervention
and judgment.

In this paper, the contour shape of bulk solids stockpile was extracted to establish a three-dimensional
model to simulate the actual stockpile. A strategy for the planning of bulk solids stcking was established
to obtain the location and volume of each bulk solids stockpile where a modified golden section
algorithm with a self-influence factor was proposed to optimize the modeling times. The flatness of the
experimental results was analyzed, from which the stacking results of the experiment and algorithm
planning were compared to explore the feasibility and effect of the planning strategy.

2. Strategy Design Of Bulk Solids Stacking

2.1 Stacking route planning

In order to reduce the equipment loss, energy consumption and the labor intensity during operation, it is
necessary to reduce the movement of the stacker in the stacking process. The loading process is
summarized as follows:

- According to the stacking site size and the total loading capacity, the stacking locations and the
  corresponding stacking volume at each stacking location are planned.
- A stacker stops at a certain stacking point for continuous loading bulk solids to form a certain size
  of a stockpile, and then the stacker moves to the next stacking point to continue loading bulk solids.

A bulk carrier with three cabins is taken as an example. The moving route of a ship loader is shown in
Fig. 1. During loading, the frequent start, stop and movement of the ship loader will affect the service life
of the equipment. Therefore, the moving route of the ship loader should be as short and continuous as
possible. After loading at one stacking location, the ship loader shall continue loading at its adjacent
location as far as possible, so as to ensure the continuity and high efficiency of loading. In addition, the
moving route of the loader must also consider the stability and strength of the ship during loading. If the
unilateral load is too large, the roll angle and trim angle of the hull will be greater than the stable value.
Based on the above considerations, the moving route of the ship loader was designed as shown in the
figure. First, 15–35% of the bulk solids is loaded from the bow to the stern along the center line of the cabin to stabilize the hull. Then, the remaining bulk solids is loaded alternately on the left or right side of the three cabins according to the double zigzag route shown in the Fig. 1.

2.2 Analysis on the stacking locations

A cabin of the above bulk carrier is selected to analyze the stacking locations. The size of this cabin is 40m * 20m * 16m, and the total loading volume of materials is 1250m$^3$. The height of stockpiles and the difference between peaks and valleys are analyzed. The results are analyzed in Fig. 2. As shown in the figure, with the increase of the number of stacking points, the slope of the height of stockpiles curve becomes gentle, and the difference between peaks and valleys decrease gradually. Furthermore, it can be observed that fewer stacking points lead to the increase in greater difference between the peaks and valleys and an uneven stacking effect. This will also cause problems such as stress concentration and unbalanced load. On the other hand, if there are too many stacking points, the stacker will move frequently, causing the decrease in operation efficiency.

The difference between peaks and valleys of a stockpile is used as a criterion for evaluating the flatness of stockpiles. According to site experience and the actual investigation, for the selected cabin with this size, the maximum allowable height difference is approximated as 4m that is shown by the green straight line in Fig. 2. With the consideration of operation efficiency and stacking flatness, the reasonable number of the stacking points should be set as 4.

2.3 Modelling of bulk solids curved stockpile

After determining the stacking locations, the next step is to calculate the stacking volume at each location. The shape of an ideal stockpile is similar to a dome cone$^{7,8,9}$, while in reality the shape of the stockpile is curved and in a non-standard geometry. Furthermore, the adjacent stockpiles overlap with each other during stacking. Thus, it is difficult to calculate the stacking volume mathematically. To model the curved stockpiles, white sand, coal and corn having five different particle size distributions are used for material stacking experiments, as shown in Fig. 3. The actual shapes of the stockpiles are created according to the experiments in SolidWorks, after which the stacking volumes can be calculated subsequently.

It can be observed from the experiment results that the bulk solids form different stockpile shapes with the variations of bulk solids types and particle sizes. Further analysis shows that the stockpile contours can be divided into three types of curves, namely the concave curve, straight curve and convex curve, as shown in the Fig. 4, showing large volume deviations to the ideal stockpiles which the slope lines are assumed to be straight.

In order to replicate the actual stockpile shape, the contour curve of the stockpile is extracted, as shown in Fig. 5. Due to symmetry, only half of the contour curve is analyzed. The origin of the coordinate is set at
the center of the stockpile, and the length of the bottom radius of the stockpile is set as 100 (dimensionless). Along the horizontal direction, a bunch of vertical straight lines is drawn with an interval of 10, after which the coordinates of the intersections of the straight lines and the stockpile curve are extracted. Then, the cross section of the half curved stockpiles are created based on the extracted point coordinates. Finally, the three-dimensional models of the stockpiles are established by rotating the cross sections accordingly in SolidWorks. Therefore, the actual curved shapes of the stockpiles formed by the coal, corn and white sand can be accurately simulated.

3. Determination Of Stacking Volume And Algorithm Optimization

The total volume of bulk solids loaded into a ship cabin is the sum of the stacking volume of the bulk solids stockpile at each location. By remaining the curved shape and adjusting the bottom radius, each stockpile is scaled until the difference between the sum of the stockpile volumes at all locations and the total volume of bulk solids to be stacked is within the allowable range. Due to the overlaps among the stockpiles, the stacking volume at each location is calculated by subtracting the overall bulk solids volume at the previous stacking location from that at the current stacking location. This calculation is repeated to calculate the bulk solids volume at each stacking location. In the process mentioned above, the determination of the bottom radius of the bulk solids stockpile requires a large number of repeated iterative calculations, so it is necessary to select an appropriate algorithm to simplify the calculation steps and shorten the calculation time.

The absolute value of the difference between the total volume of the model and the total volume of bulk solids to be stacked is taken as the objective function. When the objective function value is zero, the bottom radius of the stockpile model is the optimal solution. When the radius value is less than the optimal solution, the objective function decreases monotonically; When the radius value is greater than the optimal solution, the objective function rises monotonically. Therefore, the search process of model volume is refined as an unconstrained single valley optimal solution problem.

According to the size of the yard, the advance and retreat method is used to preliminarily determine the range of the radius value. The advance and retreat method is a optimization algorithm commonly used to determine the search space. Then, the preliminarily determined interval is divided by the golden section method to obtain the optimal solution.

The golden section method is capable of finding the optimal solution of the single valley function. In the iterative calculation process, the golden section method can ingeniously set each division point as the next golden section point, and reuse the result of the last operation, thereby simplifying the calculation. Compared with dichotomy, it has a higher efficiency in solving extreme value problems of unimodal functions. to accelerate the search step, a self-influence factor was added to reduce the number of searches during searching.
The value range of the cone radius of the stacking model is set as \([a, b]\), and the absolute value of the difference between the volume of the stacking model and the actual volume is set as the objective function \(F(x)\). The solution steps are as follows:

1. To find the minimum value in the interval \([a, b]\), let \(x_1 = a + 0.382(b - a)\), \(x_2 = b - 0.382(b - a)\), compare the size of \(F(x_1)\) and \(F(x_2)\).

2. If \(F(x_1) > F(x_2)\), then remove the interval \([a, x_1]\), let \(c = x_1\), and accelerate the new interval \([c, b]\), let \(x_1 = a + 0.382\lambda k(b - c)\), \(k\) is the acceleration trend, \(\lambda\) is the acceleration times. After acceleration, if \(x_1 < x_2\), cancel the acceleration.

3. If \(F(x_1) < F(x_2)\), then remove the interval \([x_2, b]\), let \(c = x_2\), and accelerate the new interval \([a, c]\), let \(x_2 = b - 0.382\lambda k(b - c)\), \(k\) is the acceleration trend, \(\lambda\) is the acceleration times. After acceleration, if \(x_1 > x_2\), cancel the acceleration.

According to the idea of self-influence factor in the particle swarm algorithm\(^{15,16,17}\), the improved golden section method can avoid unnecessary iterations when the valley of the curve is too close to the endpoint of the interval, so that it can reduce the number of calculations in the modeling process and the modeling time, and improve the operation efficiency of the system.

After the optimal solution of the cone radius of the stacking model was determined, the corresponding stacking model was established. The three-dimensional model is shown in Fig. 6. After the optimal bulk volume is obtained, the stacking volume of each stacking location is extracted according to the stacking route. Based on the parameters of the overall model, the model corresponding to the stacking location is first subtracted from the model of the previous stacking location, and the stacking volume of the corresponding stacking location is extracted. By repeating this process, the planned stacking volume of each stacking location is obtained.

4. Experimental Verification And Analysis

4.1 Construction of experimental platform

A rectangular single cabin model was used to perform scaled tests. The sequence of stacking locations is shown in Fig. 7. In the experiment, resin particles, volcanic stone particles, corn, soybean and unhusked rice are selected as experimental materials. Through the stacking experiment, the contour curve of the stockpile is extracted and the three-dimensional model is established. The total mass and density of each material are determined as the calculation data. The optimal stacking model is calculated by the improved golden section method, and the stacking volume related to each stacking location is calculated. The test rig geometries and material parameters are shown in Table 1. The stacking locations of the first layer start from the middle of the bow, and the material is dropped at the four points of 0.2m, 0.4m, 0.6m and 0.8m in sequence. The stacking locations of the second layer return from the middle of the stern, and
the material is dropped at the positions of 0.8m, 0.6m, 0.4m and 0.2m. Then move to the side of the cabin 0.125m away from the middle position, and drop materials at the four points of 0.2m, 0.4m, 0.6m, and 0.8m, and finally move to the other side of the cabin 0.125m away from the middle position, and drop materials at the four points of 0.8m, 0.6m, 0.4m, and 0.2m. The first layer of bedding materials accounts for 30% of the total, and the second layer accounts for 70% of the total.

<table>
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<tr>
<th>Parameters</th>
<th>Results</th>
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</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Resin particles</td>
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<td>Loading weight (kg)</td>
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<td>Cabin size (m)</td>
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</table>

4.2 Analysis of experimental results

The experimental results of the five materials are shown in Fig. 8. The height data of pile peak and pile valley measured by ideal cone model, contour curve model and experimental results are compared as shown in Fig. 9. It can be observed that compared with the ideal cone model, the measured data of the model established by the contour curve is closer to the experimental measurements, which can more accurately simulate the actual stacking situation. Furthermore, the average peak heights measured in the experiment are less than the peak heights predicted by the three-dimensional model, while the average valley heights measured in the experiment are greater than the predicted valley height. This is because the bulk solids falling from a high location will push the stockpile at the stacking location further and let them roll down from the pile peaks to the pile valleys and the sides of the box. On the other hand, due to the low mass and easy flow properties of the materials used in the experiment, the particles cannot form an ideal cone leading to smaller actual pile peak heights and greater actual pile valley heights than the theoretical values.

The flatness analysis of the peaks and valleys of each group of experiments is shown in Fig. 10 (1) to (10). The experimental data of the pile peaks and the pile valleys are averaged, and the average values of the relative errors are calculated for the resin particles, volcanic rock particles, corn particles, soybean particles and unhusked rice particles. The maximum relative errors of the peak height are 2.8%, 6.2%, 4.9%, 4.0%, and 3.1%, respectively, while the maximum relative errors of the valley height are 6.6%, 3.6%, 5.1%, 4.1%, and 5.6%, respectively. The relative error of the peak and valley heights of each group is
averaged within 5%. Therefore, the heights of the pile peaks and valleys measured experimentally only have small fluctuations in a small range, indicating good stacking flatness.

In conclusion, the pile peaks and valleys from the experiments show good flatness and smaller height differences between the pile peaks and valleys compared to the simulations. Therefore, the experiment achieves the expected balance and flat stacking effect. Moreover, similar effects are obtained for different materials. The experimental results show that the stacking strategy adopted in this paper has a good agreement, showing high accuracy with the actual bulk solids stacking. In addition, the developed model is capable of stacking various materials.

5. Conclusion

Aiming at the problem of uneven stacking of bulk solids in a rectangular ship cabin, this paper proposes a stacking strategy to achieve flat stacking of bulk solids. An improved algorithm is developed to improve the computational efficiency of the stockpile volume at each stacking location for optimal flatness. Furthermore, Experiments are conducted to verify the proposed stacking strategy. The main findings can be concluded as follows:

(1) A stacking strategy is proposed for the flat stacking of bulk solids, in which the stacking locations and the shape and volume of the stockpile at each location are considered to accurately model the actual stacking profile of the bulk solids during operation.

(2) An improved golden section algorithm is adopted for the calculation of the bulk solids stockpile at each stacking location. The search interval of the stockpile radius aiming at flat stacking is preliminarily determined by the advance and retreat method. A self-influence factor is introduced to golden section algorithm to improve the searching speed of the optimal stockpile radius and the related stockpile volume.

(3) The proposed stacking strategy is verified by bulk solids stacking experiments. The flatness of the stockpile is evaluated by the relative error of the heights of the pile peaks and pile valleys relative to their average heights. For five different materials tested, the average relative errors are within 5%, indicating the effectiveness and applicability of the stacking strategy.

Declarations

Author contributions

Jianming Yuan designed the experimental platform and developed the experimental methods. Dongxu Li was responsible for the experiment and data collection, Jiahao Yan was responsible for the drawing of charts. Jianming Yuan and Dongxu Li wrote the main manuscripts. All authors read and approved the final manuscript.
Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

References


**Figures**

![Walking route diagram of ship loader](Figure1.png)

**Figure 1**

Walking route diagram of ship loader
Figure 2

Variation chart of different stacking points number in single rectangular cabin
<table>
<thead>
<tr>
<th>Particle size</th>
<th>0.2-0.4mm</th>
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**Figure 3**

Material stacking experiment

**Figure 4**

Schematic diagram of contour curve type of stockpile
Figure 5

Schematic diagram of contour curve extraction method

Figure 6

The stacking model built by SolidWorks
Figure 7

Schematic diagram of stack position for bulk solids stacking experiment

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Figure 8

Simulated stacking experiment of different materials

(a) Height of pile peak  
(b) Height of pile valley

Figure 9

Comparison of experimental measurement data and algorithm modeling data
Figure 10

Flatness analysis results of experimental measurement data