Chen, Wei; Chen, Jian; Williams, Kenneth; Wheeler, Craig "Investigation into the ship motion induced moisture migration during seaborne coal transport." Published in *Advanced Powder Technology* Vol. 28, Issue 11, p. 3004-3013 (2017)

Available from: https://doi.org/10.1016/j.apt.2017.09.011

Investigation into the ship motion induced moisture migration during seaborne coal transport

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abstract

The inherent moisture in a coal cargo constantly migrates under the dynamic ship motion during maritime transport. The moisture often builds up at the bottom of the cargo. The accumulated water, if not removed sufficiently by the bilge well, can cause safety concerns during a voyage and difficulties dur-ing cargo unloading. The study presented in this paper aims to develop a program to investigate the moisture migration within coal cargoes in order to assess and eliminate shipping risks. The moisturemigration phenomenon is initially modelled by adopting the classic infiltration theory and considering the ship motions experienced by bulk carriers. An experimental method is developed to empirically characterise the moisture migration of a coal sample under simulated shipping dynamics. A predictive modelis also developed to estimate the total moisture migration in a full-size cargo by properly scaling up the experimental results. The model was validated by bilge well log collected from actual coal shipping voyages from Australia to international destinations.

1. Introduction

The inherent moisture within bulk material is not static during its storage, handing and transport. In fact, there is a propensity under dynamic motions for moisture to be liberated from the par-ticle assembly and becomes mobile [1,2]. This is particularly evi-dent during prolonged maritime transport processes. In many cases, the migrated moisture tends to accumulate at the base of a cargo hold under the dynamic ship motion. Fig. 1 demonstratesthe excessive moisture build-up from moisture migration after shipping voyages.

There are two major hazards associated with moisture migra- tion during shipping. Firstly, the formation of a wet base duringthe voyage can cause vessel instability and inherent safety con- cerns [3,4]. Under the International Maritime Solids Bulk Cargo Code, it is emphasized that the likelihood of formation of a wet base must be declared prior to loading onto a vessel [5]. A wet base in a coal cargo may have considerably less yield strength, and cargo shift may be triggered when significant rolling of the vessel occurs during shipping [6]. Secondly, the wet base can cause handling dif- ficulties when discharging with a grab. The excessive water at the base transforms the solids material into a fluid state, which interrupts the unloading using the grab. Although the bilge pumpis often fitted under the cargo body to enable the removal of the water drained to the base, it is critical to estimate the total amount of drained water to ensure the pumping operation is effective, in which an understanding of the moisture migration is required.

The moisture migration mechanism is closely related to the intrinsic properties of the material [7]. The infiltration theories [8–11] are often utilised to model the macroscopic moisture move- ment in unsaturated material (shown in Fig. 2(a)), such as soils andminerals. Nevertheless, these models are static state based withoutconsidering the influence of applied dynamic motions. Under external motions, the hydraulic conductivity of the unsaturatedmaterial will alter and it is difficult to accurately quantify basedon the current model development. Alternatively, from a micro- scopic view, the dynamic response of liquid bridges and capillary bonds in-between particles (shown in Fig. 2(b)) under the influ- ence of the external accelerations determine the moisture move- ment within a sample [12]. However, it is still challenging to scale up the microscopic model to describe the macroscopic mois- ture migration due to the size and shape of the real granular parti- cles. Therefore, an experimental approach remains a more direct and robust method for investigating the moisture migration mechanism.

Based on the forgoing comments, this research aims to develop an experimental program to characterise the moisture migration incoal materials under ship motions. The obtained moisture migra- tion characteristics enable accurate assessment of the water drain- ing behaviour when bulk carriers transport coals cargoes in practice.

Fig. 1. Migrated water builds up at the base of the cargo hold after a shipping journey.

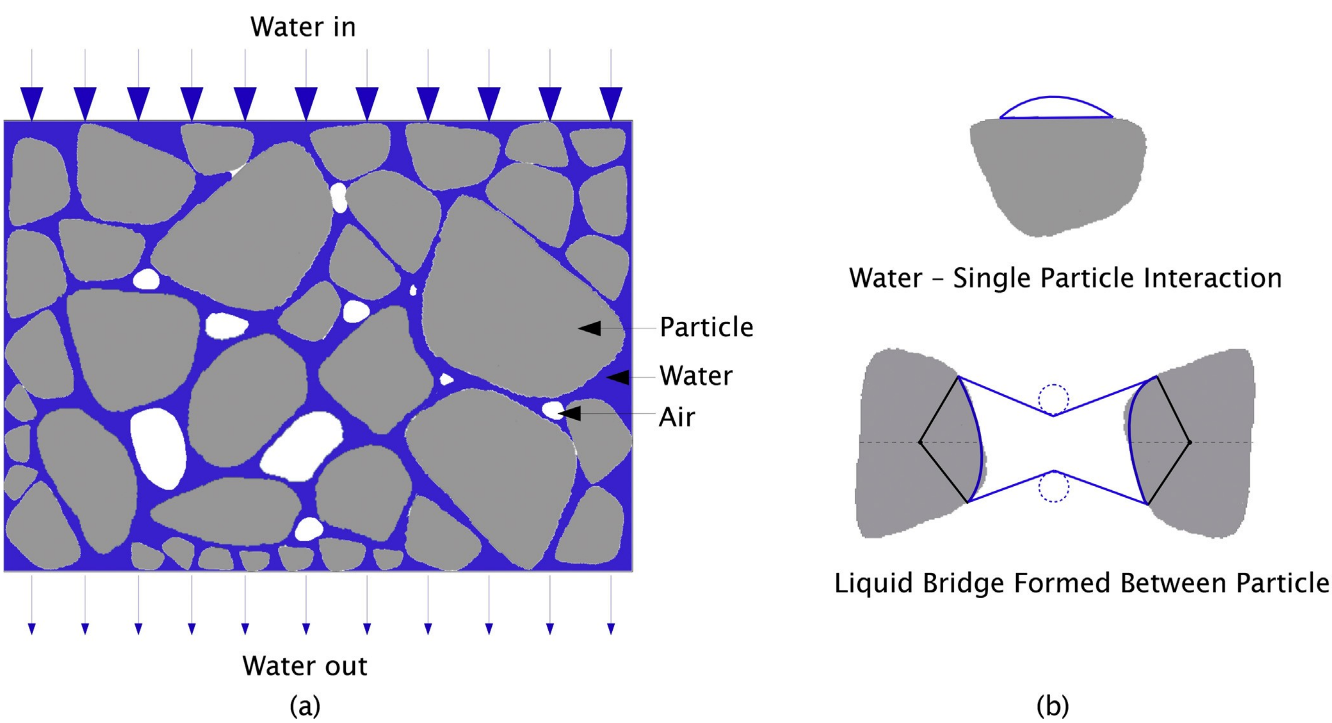

Fig. 2. Macroscopic moisture migration in bulk solids (left) and microscopic moisture-particle interactions (right).

2. Moisture migration modelling – an infiltration theory

The process of the moisture migrating within a partially satu-rated bulk solids may be described using the classic infiltration theory [13,14]. As shown in Fig. 3, considering an element within the bulk material, the speed of the moisture flowing through theelement is defined as a moisture migration rate (infiltration rate).

This moisture migration rate is depending on the following mate-rial parameters:

- The moisture content of the material – h_i,
- The hydraulic head above the element – h_0,
- The hydraulic conductivity of the material at such moisturecontent – $K\ h_i$,
- Particle and material properties such as the particle density,particle size distribution, tortuosity and porosity.

The moisture migration rate of the element is predominantly determined by its hydraulic conductivity. The hydraulic conductiv- ity of the material element is defined as [15],

$$K = k\frac{q_w g}{I} \qquad (1)$$

where

- k is the permeability of the material,

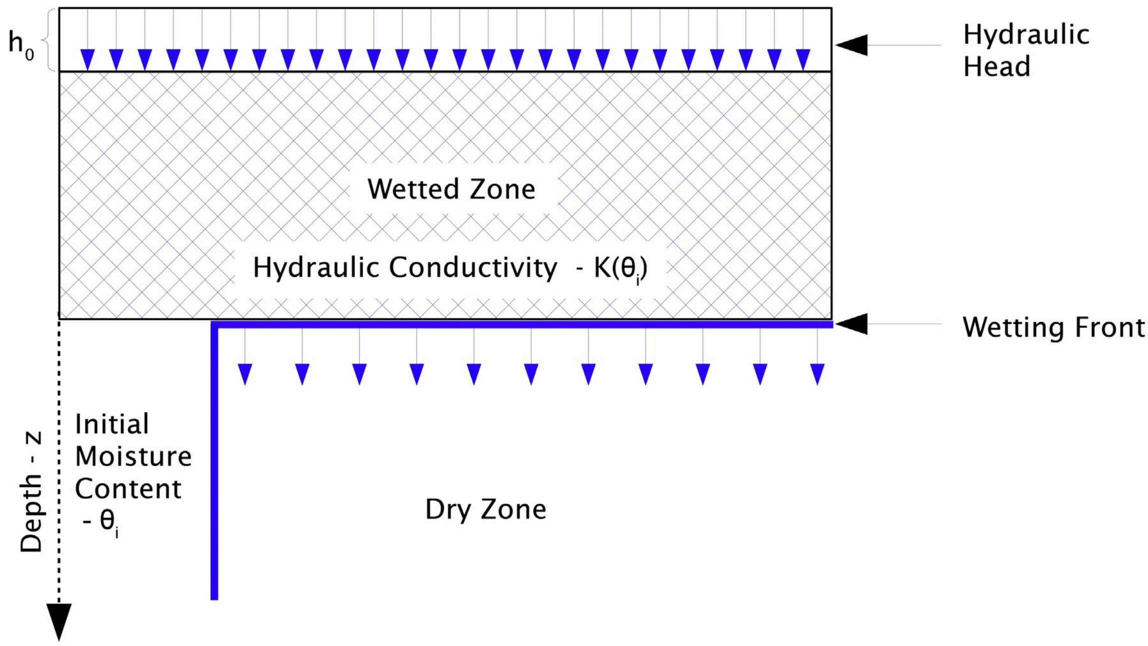

Fig. 3. The modelling of the moisture migration rate based on the classic infiltration theory.

- ρ_w is the water density,
- g is the gravity acceleration,
- μ is the dynamic viscosity of the water.

Eq. (1) is valid for moisture migration (infiltration) occurring under static conditions. Considering the bulk solids undertakesadditional motions, such as the rolling and heaving from a bulk vessel, the forgoing equation may be modified to the following expression:

$$K = k\frac{\rho_w (g + a)}{\mu} \qquad (2)$$

where a is the additional acceleration effect induced by external motions. Eq. (2) indicates that the hydraulic conductivity of the material is proportional to the applied external motions for a bulk solids with a fixed permeability. Based on the Green-Ampt theory for infiltration [13], the moisture migration rate (infiltration rate)of the material element is expressed as:

$$W = K(\theta_i)\frac{\partial h}{\partial z} \qquad (3)$$

where $\frac{\partial h}{\partial z}$ is the hydraulic gradient.

Therefore, the moisture migration rate of the bulk solids is also proportional to the applied effective accelerations. Fig. 4 shows the analytical quasi-linear correlations between the applied accelera- tion to the hydraulic conductivity and resulting total moisture migrations over time. In practical applications, however, determi- nations of the hydraulic conductivity and the moisture migration rate of a bulk solids sample remains experimentally centric due to the difficulties in theoretically deriving the tortuosity, the speci- fic surface and other parameters. The experimental approach is explicitly discussed below.

3. Ship motion considerations

Understanding the behaviour of coal cargoes and associated moisture migration behaviours during marine transportation requires knowledge of the actual forces to which the bulk carrieris subjected to during a voyage and the consequent behaviour of the vessel. Recently, a suite of comprehensive studies has been per- formed by an Iron Ore Technical Working Group [16,17] to assess ship motion of bulk carriers during marine transport. Several com- mercial bulk carriers (from Handy size up to Cape size) were equipped with instrumentations (accelerometers) to continuously monitor the longitudinal-lateral-vertical vessel motions over a per- iod of up to six months in global marine transport. Outcomes from the ship motion studies suggested that:

- The period of the natural dynamic motion experienced by bulk carriers is 10 s.
- The observed vessel accelerations are less than $1g$, typically $0.1g$ (g – gravitational acceleration).
- The ship motion induced in Handy size vessels are approxi-mately twice those of Cape size.

These findings are subsequently utilised in this study as the dynamic conditions input into the following experimentalprogram.

4. Experimental scheme

An experimental oscillatory drainage system was purposely designed to investigate the moisture migration and resulting water drainage behaviours of the coal cargoes under ship motions. As shown in Fig. 5, the experimental system is comprised of a drai- nage bench and an oscillatory frame. The drainage bench is capableof accommodating six material columns. Each material column ismade from a stack of perspex cells. The inner diameter of each cell is 140 mm and the height is 80 mm, which leads to a 480 mm high material column. Under each material column, a steel mesh layer with aperture size of 2 mm is fitted, which allows water to drain out from the material to be collected. A load cell is placed under each water collector to monitor and record the water mass changewithin the collector. Under the drainage bench, a single hydrauliccylinder drives the scissor lift structure to induce oscillatory motion of the entire system. A control system is implemented to control the vertical oscillatory acceleration and frequency through

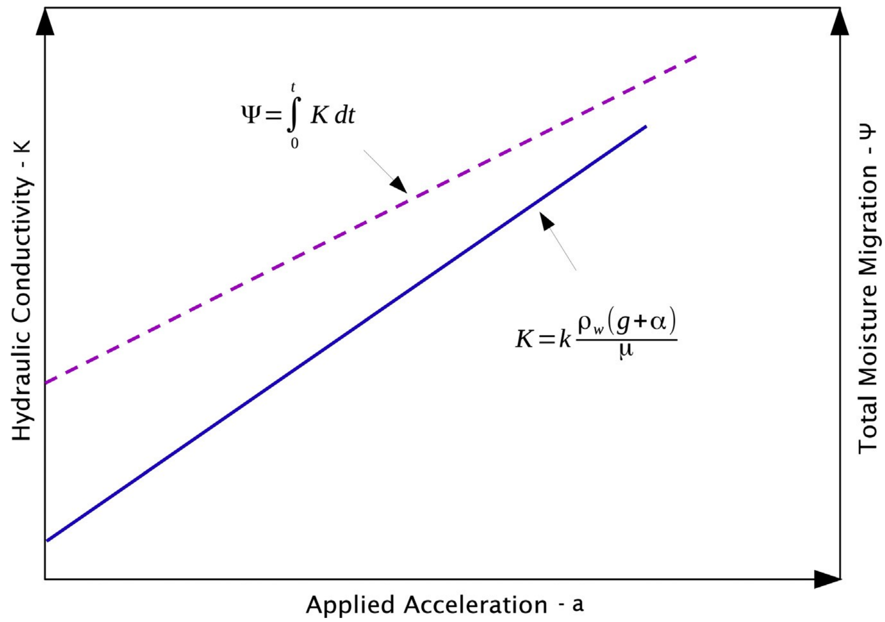

Fig. 4. Correlation between the applied motion to the hydraulic conductivity and the total amount of moisture migration.

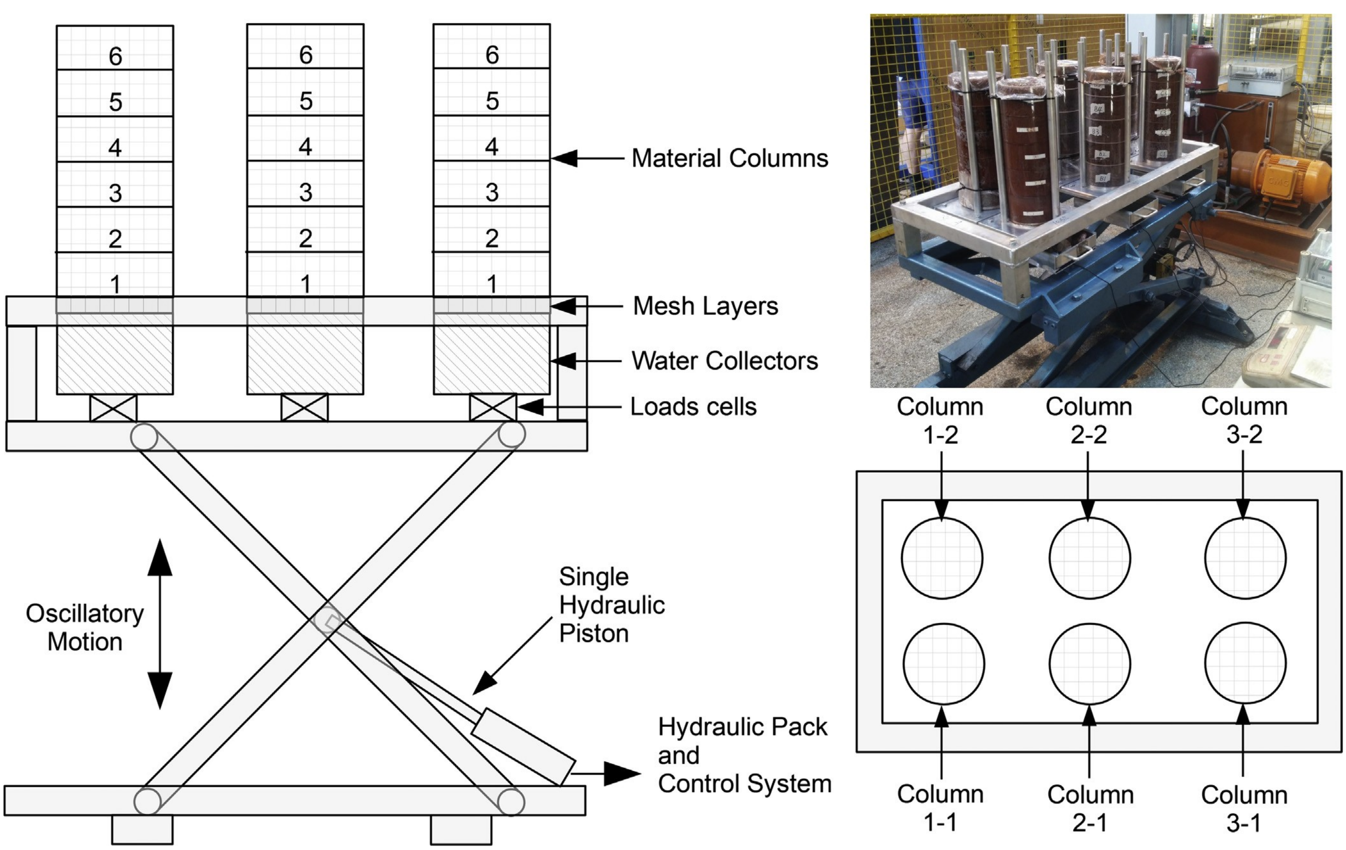

Fig. 5. The experimental oscillatory drainage system to study the moisture migration characteristics of coal materials.

a sinusoidal signal. The system is capable of inducing accelerationsup to 6 m/s^2 and frequency up to 0.6 Hz.

4.1. Sample properties and specimen preparation

A coal material which exhibited moisture migration behavioursduring marine transport was selected for this study. The general

Table 1
Material properties of the selected coal.

Particle Density – kg/m^3	1380
Transportable Moisture Limit [5,20]	13.4%
Typical Size Range – mm	0.045 ~ 50

material properties are shown in Table 1. The typical top size onboard the bulk carrier is 50 mm. Where bulk solids are composedof particles of a large size range from coarse to fines, it is the fineparticles that hold the majority of the moisture, in particulate, coal materials [18]. Therefore, to maintain the cell inner diameter to be larger than at least five times of the maximum particle size to elim-inate the wall effect [19], a sample reconstitution process was performed.

The principle of the sample reconstitution is shown in the flow-chart in Fig. 6. The reconstitution process commences by sievingparticles larger than 25 mm and smaller than 25 mm. Coal parti-cles in the size range of +16 mm to 25 mm size are extracted fromseparate subsamples and reconstituted back into the original25 mm screened coal based on a mass equivalent to the +25 mm sized coal removed from the initial sample to provide a final reconstituted sample of sufficient mass for testing. By this means, the 16 mm material content is maintained as per the orig-inal 50 mm sample. The particle size distributions of the original sample and reconstituted sample are shown in Fig. 7.

When preparing the test specimen in each cell to form material columns, the compaction state was critical and should be selectedto be reflective of the compaction state in an actual cargo hold. The Proctor/Fagerberg compaction method was suggested by the Inter- national Maritime Organisation [6,20] to achieve a compaction state reflective of the in-hold conditions. Therefore, this com- paction method was adopted to prepare the test specimen in the current work.

Three initial moistures contents (wet based) selected, being 10.0%, 11.5% and 13.0%. These moisture values were selected basedon the historical as-loaded moisture data of this coal sample.

4.2. Testing procedures

At the beginning of a test, the loads cell measurement was ini- tiated, after which the material column was prepared following the Proctor/Fagerberg compaction method. Within each test, the mate- rial columns were prepared as followings:

- Column 1-1 and Column 1-2 for 10.0% samples
- Column 2-1 and Column 2-2 for 11.5% samples
- Column 3-1 and Column 3-2 for 13.0% samples

All material columns were sealed after the specimen prepara- tion process to prevent moisture loss. Then, the hydraulic systemwith preferred motion settings was set and switched on to oscillate the entire system continuously. The oscillation was stopped whenno further increment of the mass in all water collector trays wereobserved based on the loads cell readings. The specimen in each cell was retrieved and dried in an oven for moisture analysis. Threetests under different accelerations were selected based on the ship motion study discussed above, which were

- gravity acceleration (g) only (static drain),
- gravity acceleration (g) plus average ship heaving acceleration (0.1g) for a Cape size vessel,
- gravity acceleration (g) plus double the average ship accelera-tion (0.2g) which was assumed to be motion experienced by a Handy size vessel.

An oscillation frequency of 0.5 Hz was selected to input into the testing system instead of using the ship motion frequency of 0.1 Hz. This essentially led to the sample being subjected to five times the total oscillatory motion cycles within a fixed time period. The selection of such a frequency is aiming to accelerate the overall testing duration, as well as maintain the mechanical integrity ofthe system. The influence of the increased frequency can be min-imised by normalising the amount of the moisture has migrated to a per motion cycle basis.

5. Results and discussion

5.1. Moisture migration characterisation

The water drainage results from the material columns under different accelerations are shown in Fig. 8. It is evident that the water drainage from the coal sample is dependent on both the

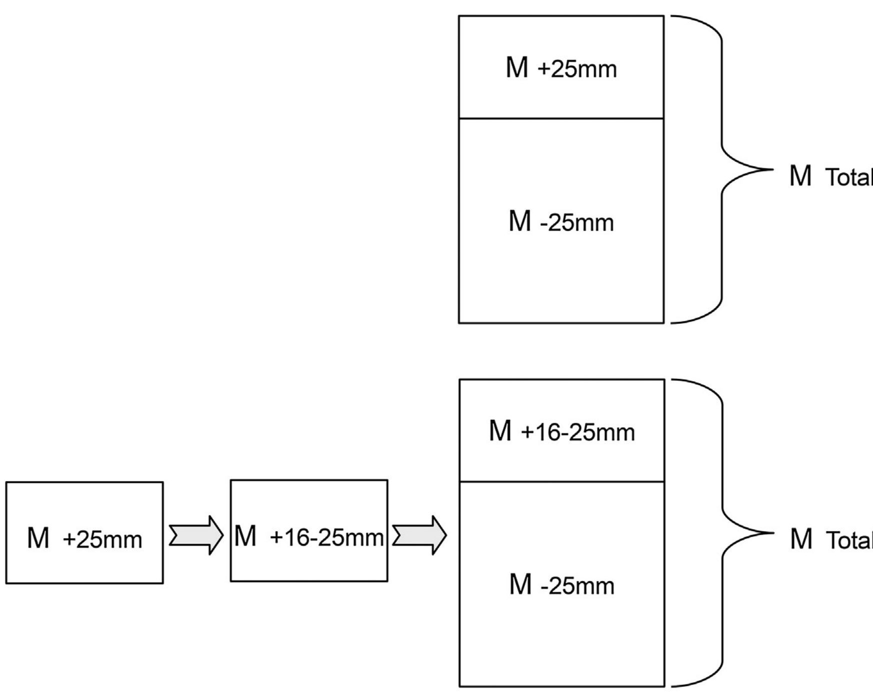

Fig. 6. Principle of the sample reconstitution.

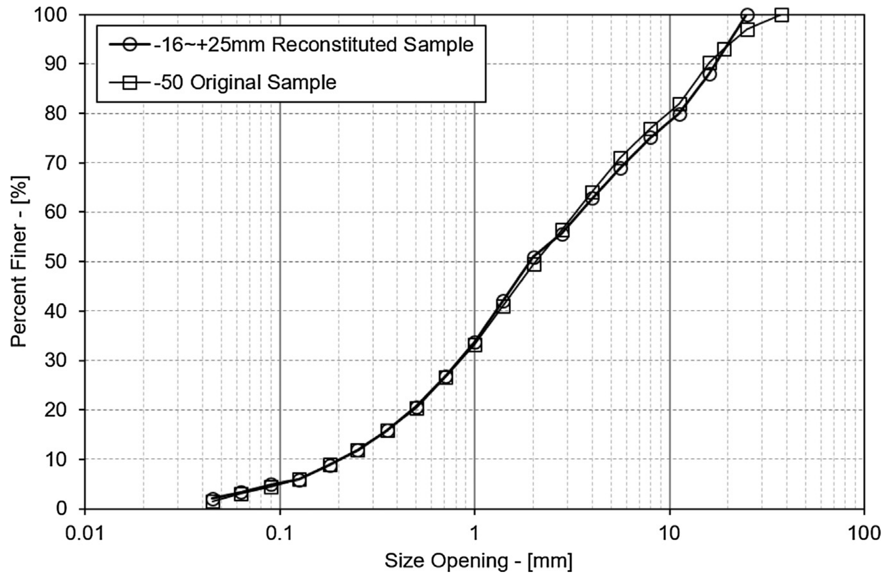

Fig. 7. Particle size distributions of the original and the reconstituted samples.

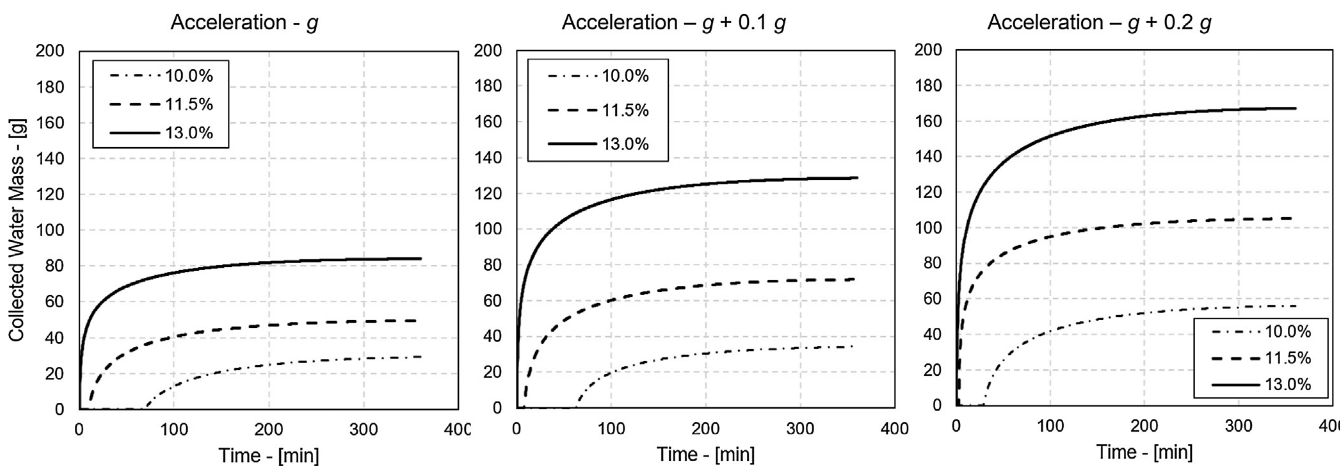

Fig. 8. Water drainage curves of tested coal samples with different initial moisture contents under increasing accelerations.

initial moisture content and the applied acceleration. Essentially, under a fixed acceleration, drainage commenced earlier for higher moisture samples compared to lower moisture samples, which also resulted significantly more total water drainage before reaching a steady state. Meanwhile, when comparing coal samples with the same initial moisture under increasing accelerations, it is evident that water drainage increases with increasing acceleration.

Additionally, the moisture profiles after testing in all material columns are shown in Fig. 9. From the figure, obvious moisture migration towards the base is observed in all tests. Comparing the moisture profiles in samples with the same starting moisture,it is clear that relatively drier samples are obtained under higher

accelerations, suggesting enhanced moisture migration occurred.

Nevertheless, when increasing starting moistures, but keeping aconstant acceleration, the resulting steady state moisture profiles

in all material columns are similar.

Overall, the experimental results suggested that the moisture migration and associated water drainage from coal sample depends on both the initial moisture and the applied acceleration. Generally, increasing the initial moisture and the applied accelera- tion promotes the moisture migration process. Practically, the results indicated that more bilge water will be obtained at higher

as-loaded moisture, and/or when vessels experience large swellsduring transport.

5.2. Water drainage modelling

To further quantify the effect of the initial moisture and the applied acceleration on the moisture migration characteristics ofthe coal sample, a drainage rate (W) was formulated to describethe speed of water draining from the material column due to mois- ture migration when undertaking a period of applied motion. W is defined as,

$$W = \frac{M_{ssw}}{N_{cyc}} = \frac{M_w}{T_{ss} \cdot f} \tag{4}$$

where M_{ssw} is the drained water mass at steady state, taken as 95% of the total water mass drained out of a material column from a water drainage curve. N_{cyc} is the total number of cycles that the sample has undertaken the applied motion until reaching the steady state; and can be calculated using T_{ss} and f, which are the testing time elapsed when reaching the steady state and the motion frequency (0.5 Hz in the test).

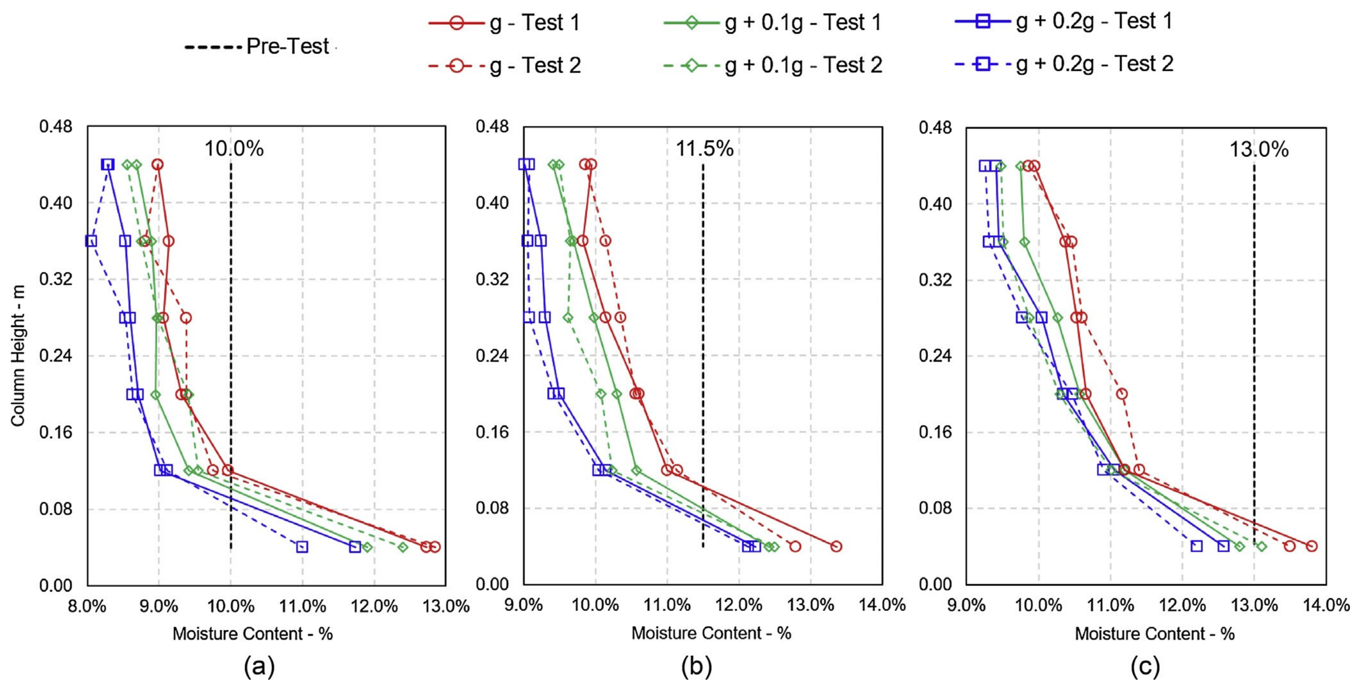

Fig. 9. Moisture profiles of material columns under different initial moistures and accelerations.

Table 2
Water draining rate under different initial moistures and accelerations.

Initial moisture	Acceleration – m/s²	Drainage rate – mg/cycles
10.0%	g	0.57
	$g + 0.1g$	1.07
	$g + 0.2g$	1.96
11.5%	g	1.94
	$g + 0.1g$	2.96
	$g + 0.2g$	5.45
13.0%	g	4.42
	$g + 0.1g$	6.75
	$g + 0.2g$	8.76

Based on Eq. (4), calculated drainage rates for all test samples are shown in Table 2 and plotted in Fig. 10.

As shown in Fig. 10, the drainage rate exhibits a quasi-linear trend with the applied acceleration under a fixed moisture, which can be expressed as:

$$W = A\,a + B \tag{5}$$

Such a trend coincides to the analytical moisture migration shown in Fig. 4. The function coefficients A and B in Eq. (5) can be empirically correlated to the initial moisture. As shown in

Fig.10(b) and (c), quasi-linear correlations are evident between the function coefficients and initial moistures. Following the aboveanalysis, the coefficients of Eq. (5) are derived as:

$$A = 49 \cdot MC - 4.09 \tag{6}$$

$$B = 132.33 \cdot MC - 12.99 \tag{7}$$

5.3. Modelling bilge well water mass for full scale cargoes

Based on the lab scale moisture migration test discussed above, the moisture migration process and the resulting bilge water build- up in a full scale coal cargo during marine transport is modelled as follows. As shown in Fig. 11, a loaded cargo can be discretised into a series of cargo elements. Each cargo element is comprised of a large number of infinitesimal elements. An infinitesimal element is assumed to be equivalent to a material column in the lab scale oscillatory drainage testing system.

Providing there is a constant moisture migration and a water drainage rate for the loaded material, the infinitesimal element remained in an equilibrium state since it was receiving and drain- ing the same amount of water. Therefore, the total mass of migrated water flowing into the bilge well can be estimated as

$$M_{Bilage} = N_{CE} \cdot W \cdot T \cdot f \tag{8}$$

where N_{CE} is the total number of cargo element based on the as- loaded mass. W is the averaged drainage rate at as-loaded moisture and can be interpolated based on Eqs. (5)–(7). T is the duration of marine transportation and f is the frequency of the ship motion(0.1 Hz based on a 10 seconds natural ship motion period).

As regulated by IMSBC Code [5], trimming of the cargo is per- formed after loading to ensure the surface is relatively flat. There- fore, based on a flat cargo surface and a uniform bulk density, N_{CE} isderived as

$$N_{CE} = \frac{M_{loaded}}{M_{CE}} = \frac{\rho_B V_{loaded}}{\rho_B \pi R^2 H} \tag{9}$$

where V_{loaded} is the as-loaded cargo volume, R is the radius ofthe infinitesimal element and H is the as-loaded cargo height. The loaded cargo volume V_{loaded} and the loaded cargo height H are easily obtained after the loading stage by the vessel surveyor.

5.4. Model validation – Australia to International destinations

To validate the proposed model for bilge water prediction, twoshipping journeys of Cape size vessels carrying the studied coal material are utilised. Details are:

- Australia to Vietnam: The shipping route originated from the East Coast of Australia in the Coral Sea, and after passing the East Coast of Papua New Guinea and West Coast of the

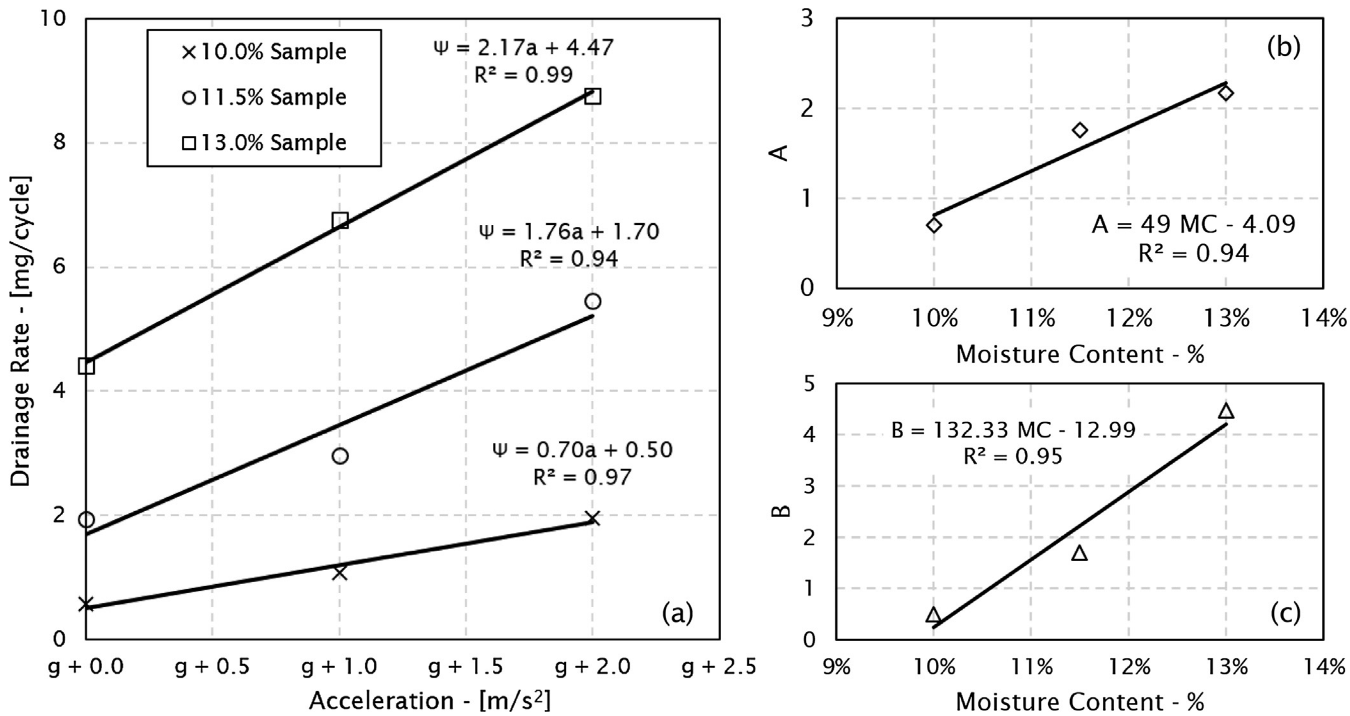

Fig. 10. Empirical formulations of the water drainage rate and its associated model parameters for the tested coal sample.

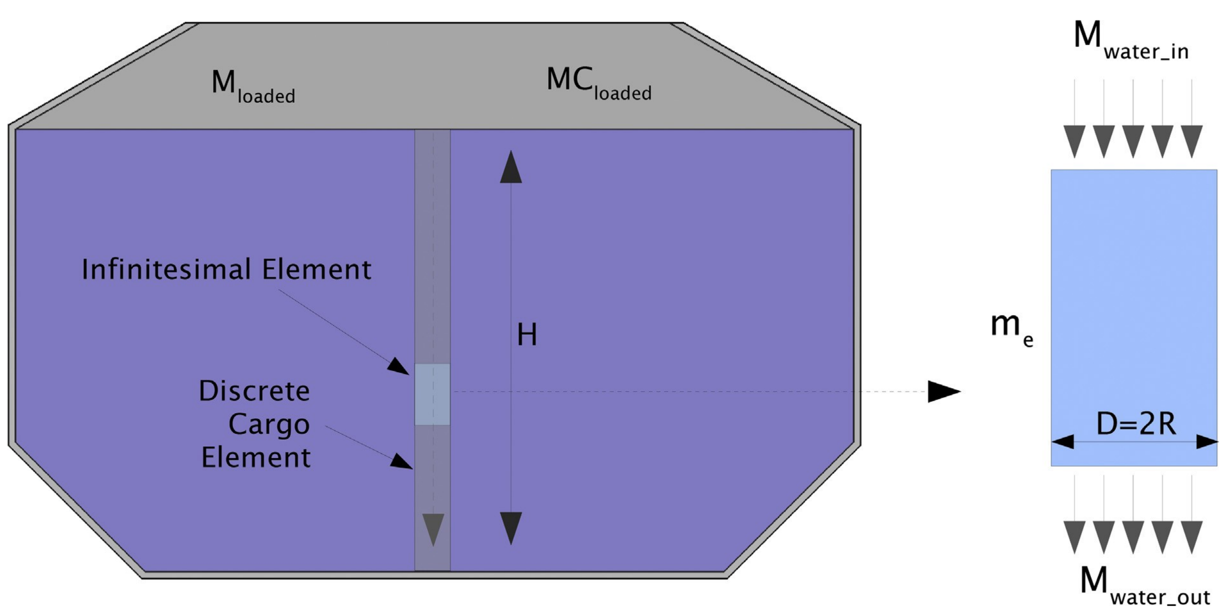

Fig. 11. Modelling of the moisture migration and associated water drainage behaviours for the full size cargo.

Philippines, the vessel arrived in Vietnam after 15 days of mar- ine transport. Hatches 2, 4 and 6 were loaded with the studied coal material.

- Australia to United Kingdom: The shipping route originatedfrom the East Coast of Australia in the Coral Sea, and after pass-ing Bass Strait between the States of Victoria and Tasmania, the vessel sailed through Great Australian Bright, then, towards Indian Ocean. The vessel then continued around Cape Town of South Africa in South Atlantic Ocean. After passing the Equatorand the North Atlantic Ocean, the vessel arrived in Redcar, United Kingdom after 69 days of sailing. Hatched 1, 3, 7 and 9 were loaded with the studied coal material.

The water mass drained into the bilge well was monitored andrecorded daily, and the bilge well was emptied once it was full. The as loaded properties of each cargo in the two journeys are shown in Table 3.

The cumulative drained water mass flowing into the bilge wellfor all cargos in each journey is shown in Fig. 12. It is evident from the graph that there is a quasi-linear correlation between total water drainage to time, which agrees with the forgoing theoretical analysis. In addition, more loaded cargo mass led to comparatively more water recorded in the bilge well.

Based on the as loaded cargo properties, the prediction for the drained water flowing into the bilge well for all cargoes is per-

Table 3
The as loaded properties of each studied cargo.

Journey Title	Hatch Number	As-loaded Moisture	Total Tonnage – tons	Total Volume – m³	As loaded bulk density – kg/m³	Cargo Height – m
Australia to Vietnam	2	10.9%	13,699	12,614	1086	17.38
	4		10,908	10,044	1086	14.08
	6		13,890	12,790	1086	17.60
Australia to United Kingdom	1	11.5%	16,759	15,194	1103	19.99
	3		19,821	17,970	1103	22.75
	7		19,791	17,943	1103	22.86
	9		16,256	14,738	1103	19.65

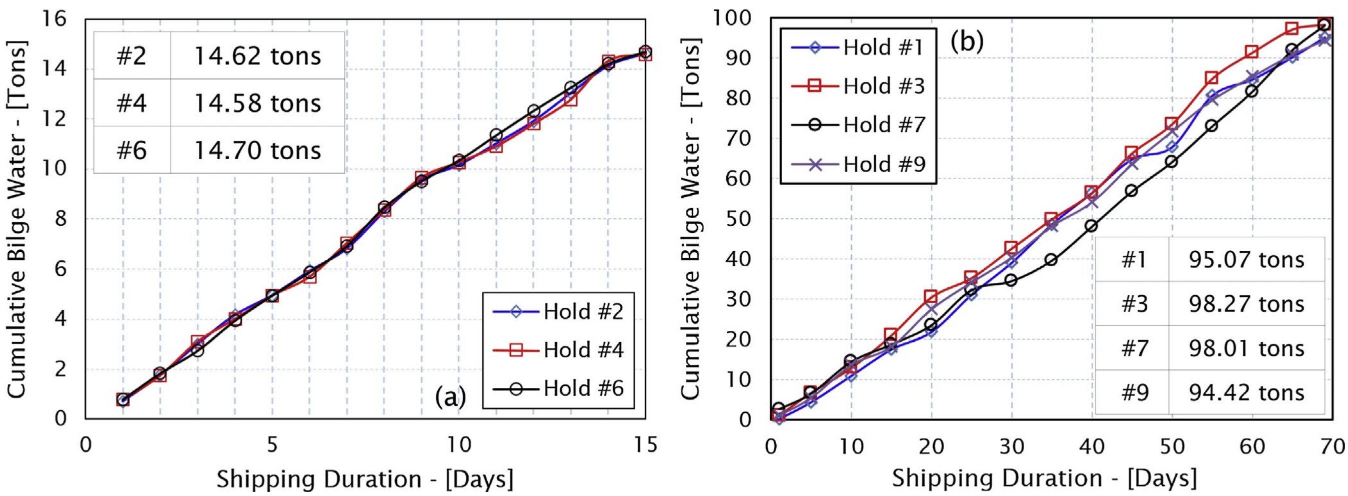

Fig. 12. Daily and total drained water tonnage flowing into the bilge well under each cargo hold in the studied vessel.

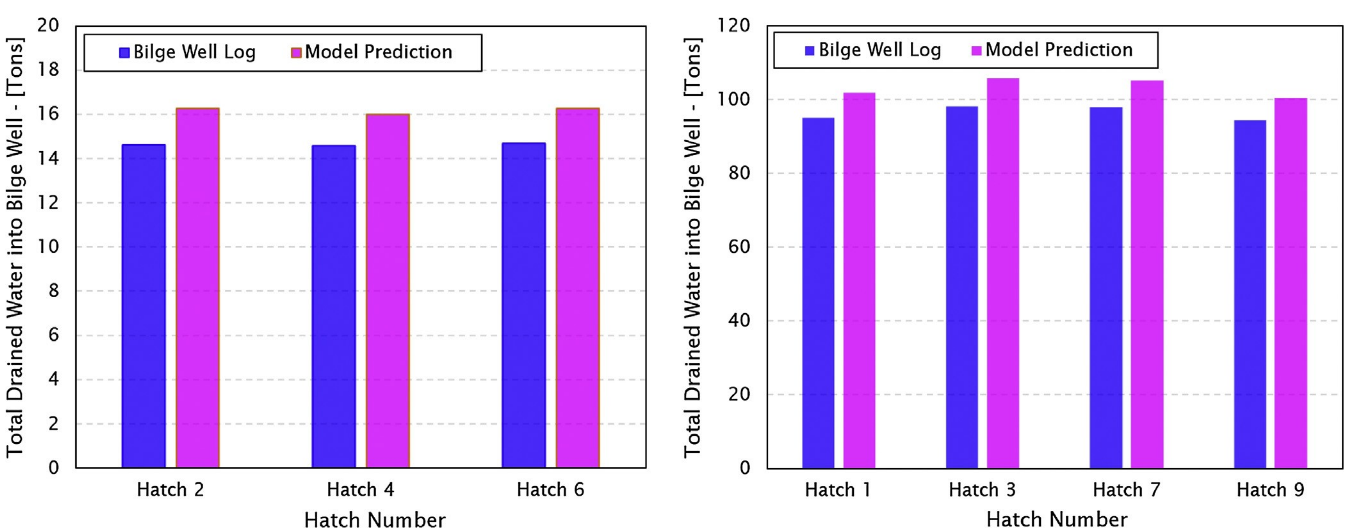

Fig. 13. Comparison between the measurements from the bilge well log and the model predictions.

formed. Initially, based on the as-loaded moisture, the average drai-nage rates of the coal material are estimated using Eqs. (5)–(7) as,

- 2.68 mg/cycles at the as-loaded moisture content of 10.9%under $g + 0.1g$ constant ship motion
- 3.46 mg/cycles at the as-loaded moisture content of 11.5%under $g + 0.1g$ constant ship motion

Additionally, the total cargo elements based on the loaded cargovolume were calculated using Eq. (6), with the following results:

For the vessel from Australia to Vietnam,

- N_{CE}: 47,147 for hatch 2
- N_{CE}: 46,340 for hatch 4
- N_{CE}: 47,208 for hatch 6

For the vessel from Australia to United Kingdom,

- N_{CE}: 49,371 for hatch 1
- N_{CE}: 51,319 for hatch 3
- N_{CE}: 50,995 for hatch 7
- N_{CE}: 48,721 for hatch 9

Higher as-loaded cargo mass led to more cargo elements in thepredictive model. Therefore, the total water mass flowing into thebilge well for each cargo can be estimated using Eq. (8) based onthe maritime transport duration and 0.1 Hz natural ship motion frequency. Results of the predictions are shown in Fig. 13 in com-parison to the accumulated water tonnage obtained from the bilgewell log. The model predictions are observed to be slightly largerthan the results from the bilge well log, most likely due to that some excessive moisture is still held at the base of the cargo. Prac- tically, residual water is often observed at the base of the cargo during unloading. Overall, the model prediction shows good agree- ment with the bilge well log data.

6. Conclusion

This research presented a study on the moisture migration ofthe coal material on-board bulk carriers during marine transport. A suite of analytical, experimental and validation studies was con- ducted. The outcome of this study yielded the following major findings:

- The classic infiltration theory can be applied to model moisture migration of coal cargoes under ship motions.
- The total moisture migration within coal cargoes under ship motion is dependent on the initial moisture, the ship motion and the time.
- The oscillatory drainage system can be applied to a broad range of coal materials to obtain the parameter characterising themoisture migration characteristics.
- The developed cargo moisture migration model showed good agreement between predictions and actual bilge well log results.

Consequently, the outcome of the study can be directly applied to the shipping industry for safer maritime journeys and more effi- cient discharge at the unloading port.

Acknowledgement

The authors are grateful for the financial and technical support from Anglo American Metallurgical Coal Pty Ltd.

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