8 Read the passage below and answer the questions that follow.

Building the pyramids

The Egyptian pyramids and the Great Sphinx of Giza rise out of the desert on the outskirts of Cairo as a legacy to a long-lost civilisation. The largest pyramid, the Great Pyramid of Giza, built for the Pharaoh Khufu in around 2530 BCE, was the tallest building on Earth until Lincoln Cathedral was erected in 1311. The pyramid projects a dazzling white figure against the desert, having 53000 outer casing blocks of quality limestones where its density is about 2600 kg m^{-3}.

The Great Pyramid is 147 m high and its square base has sides of 230 m. It is made up of around 2.7 million limestone blocks. These limestone blocks vary in size with an average mass of each limestone block estimated to be around 2.5 tonnes where 1 tonne is equivalent to 1000 kg.

According to the Greek historian Herodotus, it took 100 thousand men 20 years to build the Great Pyramid while the physicist Mendelssohn estimated that only about 13% of that workforce was involved in lifting the limestones. The work done in building such a structure is equivalent to raising all the material to its centre of mass which, in the case of a pyramid, is a quarter of its height.

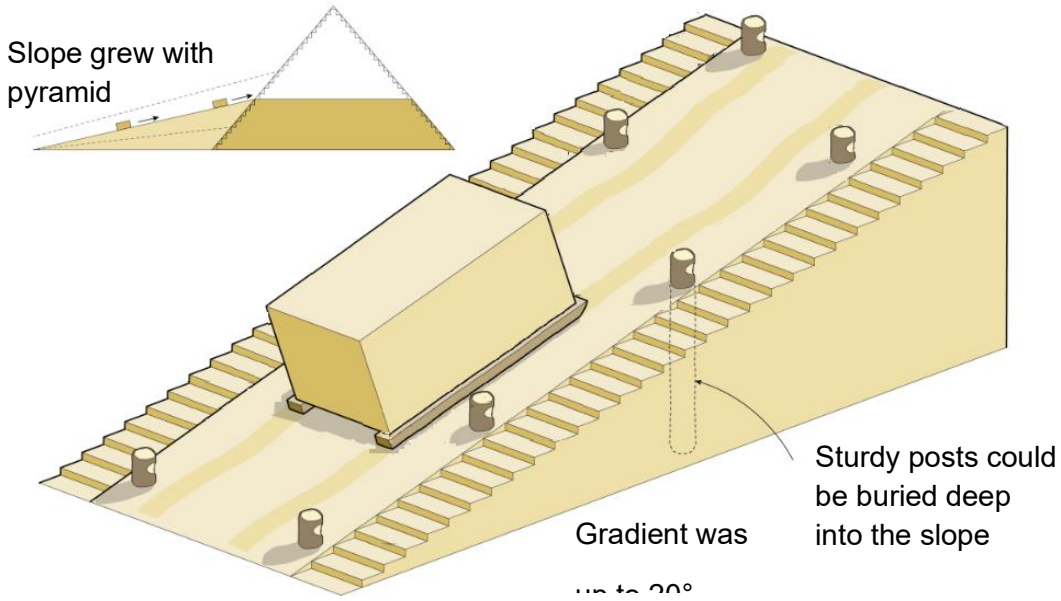

Fig. 8.1 (Source: Khalil, M. Methods of Pyramid Construction)

In 2018, an Anglo-French team discovered an ancient ramp at the site of the quarries at Hatnub, providing the evidence that ramps could be used to drag limestones from the quarry to build the

pyramids. The linear ramp has an incline of 20° with steps either side, and holes that could allow sturdy vertical posts half a metre in diameter to be buried in them as shown in Fig. 8.1.

A typical man today obtains around 2500 kcal of energy per day from food where 1 kcal is equivalent to 4.18 kJ. After considering the energy required to stay alive, there is 870 kcal of energy left for doing physical work. Research on factory workers suggests that humans are about 20% efficient when performing manual tasks. These figures can be used to apply to the ancient Egyptians to estimate the workforce needed to build the Great Pyramid.

(a) The volume V of a pyramid is related to its height h and a square base with side length b by the following equation:

$$V = \frac{1}{3}b^2h$$

Hence, if the limestones could be lifted into position, determine the work done in building the Great Pyramid.

work done = …….. J [2]

(b) Evidence suggests that various ramp configurations were used to construct different pyramids, including the Great Pyramid.

Assuming a linear ramp with a 5.0° incline was employed, the friction played a significant role in dragging limestone blocks up the ramp. The friction f acting on the limestone block is proportional to its normal force N which is given by

$f = \mu N$ where μ is the coefficient of sliding friction between two surfaces.

When limestone blocks are dragged up a limestone ramp, the coefficient of friction for limestone against limestone is 0.75.

(i) Explain why dragging limestone blocks up a slope involves doing more work than lifting them.

……

…… [1]

(ii) On Fig 8.2, draw a labelled free-body diagram, showing all the forces acting on the limestone block as it is being dragged up a slope.

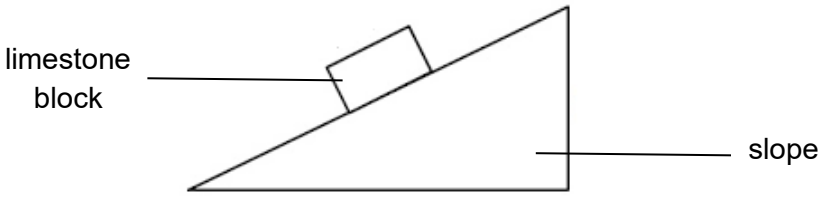

Fig. 8.2 [2]

(iii) Determine the friction acting on the limestone as it is dragged up at constant speed.

friction = …….. N [2]

(iv) Hence, show that the force needed to drag a limestone block is 2.0×10^4 N.

(v) With such a large dragging force needed, suggest how having sturdy vertical posts in buried deep into the slope could make it easier to drag the limestone blocks up.

……

…… [1]

(c) **(i)** Determine the work done in dragging all the limestone blocks up a ramp of 5.0° through a quarter of the height of the Great Pyramid.

work done = …….. J [2]

(ii) Hence, estimate the number of people needed to drag the limestone blocks up and complete the Great Pyramid in 20 years.

number of people = …….. [2]

[Total: 13]

End of Paper