Managing Block Paver Gap Performance: a modelling solution

Margaret Mackisack, Queensland University of Technology, Australia

Charles Pywell, ABEX Management Services, Australia

Summary
This paper describes a model which enables factors affecting the size of gaps between block pavers laid in herringbone bond over a large area to be investigated. The behaviour of rectangular and dentated shapes is compared through simulation, and the influences of block design, manufacture and laying variables are discussed. The model shows that gap performance is highly dependent on block shape and the value and variability of block parameters.

1. Introduction

This study arises from practical difficulties experienced in laying concrete segmental paving blocks in herringbone bond (HB) in an application where the gap sizes need to be closely controlled over a large area. The gaps, which are subsequently filled with sand or other stabilising material, are required to be not too small, (otherwise the blocks may touch, causing spalling); nor too large, (otherwise the structural integrity of the pavement may be lost) [1]. The aim of the study is to define and investigate the parameters which need to be controlled in the design, manufacture and placement of the blocks so that the HB pavement will satisfy specified minimum and maximum gap size criteria.

Conventional engineering custom and aesthetic considerations prefer that the lines determined by the block edges should be 'straight'. Furthermore, recent design specifications include spacer nibs of specified minimum dimensions on certain block faces to ensure that minimum gap sizes are achieved. It is therefore necessary to investigate to what extent these further constraints are compatible with the allowable gap size criteria.

The paving pattern colloquially called HB (Figure 1, with no gaps) is one of several well-known regular tessellations. Close examination of a real pavement made of blocks laid in HB reveals that, as well as the skeleton of the tiling, complex pattern structures are generated by the gaps between the physical blocks (Figure 2, and see also [2]).

2. Expectations and Achievements of the Model

The model was designed to improve understanding of the process involved in laying segmental block pavers through a rigorous analytical process, using qualitative results and visual effects initially. It had to be flexible with regard to input parameters and data, capable of representing large areas of paving, and executable on appropriate personal computers. The initial expectation was for modelling of rectangular blocks only. The model described in this paper achieves all of the above expectations, and also includes a capability to model dentated pavers.

3. Modelling Features of Physical Blocks

In principle, HB can be laid in suitably shaped blocks with any 1:integer proportions, but the majority of commercial pavements use blocks nominally 1:2, approximately the size and weight of ordinary house bricks, 95-115 cm wide and 195-215 cm long. This study is concerned with rectangular blocks (Figure 3) and a version of the Type A interlocking block (Figure 4), both with spacer nibs cast on some of the block faces. The thickness of the blocks is ignored, so that only the plane pattern on the surface of the pavement is considered.

Considering first rectangular blocks, if the physical block length is denoted L and the breadth B, then the design gap DG is defined to be DG=(L-2B). Blocks of dimension L by B laid with gaps DG between them will form a perfect herringbone pavement with all gaps of the same size and all block edges lying on straight lines. The model therefore supposes a rectangle L units long, B=(L-DG)/2 units wide, and with nibs N units in dimension on each face, as shown in Figure 3.

The second type of block investigated is dentated, and its shape is defined by two angles α and β,

the length of the side D and the ratio of sides D:C, as in Figure 4. Cutting a strip of width DG/2 from the edge of the basic block shape generates physical blocks which, if laid with gaps DG between them, will again form a perfect herringbone pavement. A hypothetical set of parameters were chosen to define the shape to be investigated; again, nibs N units in dimension were supposed to be placed on certain faces, as in the Figure.
Comparison between rectangular and dentated block behaviour was facilitated by 'matching' the size of the blocks, so that a dentated block was considered to be equivalent to a rectangle of the size shown by the shadow rectangle in Figure 4.
Concrete paving blocks are made in case-hardened steel moulds which are subject to considerable forces during moulding, and to abrasion. Irregular wear causes the actual dimensions of the blocks produced to change unpredictably over the life of the mould. As well as mould wear, changes from batch to batch of the input mix, the atmospheric and curing conditions, personnel and other imponderables add to the random variation in block dimensions. Perhaps in recognition of this, current standards for allowable variation in manufactured block size permit a considerable range in the finished block dimensions.
Historically much more attention has been paid in Australia to ensuring adequate block strength and surface finish than to dimensional stability. Practices have been developed by the block laying trade in an attempt to overcome variability problems, such as mixing blocks from different lots on site so that the variation is evenly spread. This reduces the chance of intense localised variation being introduced into the pavement, but increases overall variation in any particular area. One of the key objectives and advantages of the modelling process which has been developed is its capability to reflect the effects of dimensional variability in the blocks. Accordingly, suitable random variables have been defined for each of the two block shapes under consideration which enable typical production variation to be simulated.

4. Modelling Laying Herringbone Pavement

There are three sequences for laying blocks which create long diagonal faces, referred to below as method 45, method 31 and method FB, illustrated in Figure 5. An important practical constraint satisfied by these methods is that no block is ever placed in a trapped position (all blocks have two free sides when placed). Shackel [3] and Lilley [4] describe methods 45 and 31, the two procedures for which blocks are laid always in the same direction, as suitable for situations where more than one operator is working on the face. However, with some care in dealing with isolated trapped blocks when using multiple operators, all three procedures are in common use for large scale paving and have thus been included in our investigations.
There are many boundary conditions which might be of interest for HB pavements, but for the application of interest to the authors a pair of boundaries on the south and east edges of the pavement were required. These were variously constructed to simulate the presence of a straight edge construction joint, or to simulate interface with an existing herringbone pavement. Potentially, these boundary conditions enable the modelling of very large areas of pavement using rectangular subregions. They also enable comparison of laying a triangular region with a single long face for the pavement, or of laying a sequence of smaller contiguous squares.
When placing a rectangular block into a growing HB pavement, the long and short sides can be placed independently. The short side of each block adjoins the long side of a previously placed block, while the long side adjoins two previously placed blocks.
The dentated block shape has more complex geometry which means that the positions of the long and short sides cannot be adjusted independently. An algorithm has been developed which computes an optimal position for a dentated block relative to the previously laid blocks, ensuring that any minimum gap constraints are met, and allowing a pavement consisting of a large number of variable blocks to be automatically simulated.
There are two schools of thought about how blocks are actually placed which find expression in block paving literature and practice. The first affirms that a good operator aims to keep gap sizes relatively constant, and implies some fixed size target gap being aimed for by the blocklayer. The second says that the block is placed in contact with the previous blocks, and allowed to fall into

place ([3] p 205). This latter method suggests the introduction of a further element of randomness to accommodate the variation implicit in the idea of falling into place. The model is capable of simulating both of these dicta for rectangular blocks, while at present the algorithms for dentated blocks simulate only the second procedure.
The model simplifies some aspects of real blocklaying practice. For example, it simulates the placement of one row of blocks at a time, according to predetermined algorithms, and makes no allowance for subsequently adjusting blocks (using string lines, according to construction practice). While this may appear to be a limitation, it is important to realise that the results obtained from the model show that discrepancies which may have an important subsequent effect on the pavement may not be discernable even to an expert eye, and that practical experience shows that attempts to fix up more than extremely small areas of pavement meet with little success. Further, the development of block/laying/gap specification parameters which facilitate the laying of a large area of paving successfully in a single pass without revision would be commercially desirable.

5. Numerical Simulation of the Gaps Between Blocks

Computer code for the model as described above has been written in Fortran for IBM-compatible PC's. Assessment of the sensitivity of pavement performance to varying input parameter combinations is achieved by monitoring maximum gap size, number of gaps over 5mm, and percentage of gaps between 4mm and 5mm, in simulated areas of equal size. Displays of experimental results produced by the simulation show the locations of gaps in the 4mm-5mm and over-5mm size classes, while other graphical summaries are produced from post-processing of the simulation results.
A sequence of factorial experiments has been carried out to identify those regions of the parameter space determined by block length, design gap, nib dimension, and block and nib variance, within which acceptable HB paving appears to be produced. The selected results presented here demonstrate some of the interesting features of the dentated blocks, and indicate where the optimal parameter combinations appear to lie for the particular shape analysed. Results for rectangular blocks with the same parameter combinations are shown for comparison.
More extensive experimentation carried out to date with rectangular blocks has shown that there is not much difference in gap performance between the three different laying methods simulated. The results below for dentated blocks are for laying with method FB, and it is by no means clear that the results for othe laying methods using dentated blocks would be similar. Further model development is being undertaken to investigate this question. For the rectangular configuration, laying blocks with the objective of achieving a constant size gap between blocks will produce a consistently better product than laying blocks up against nibs. The results for rectangular blocks shown below for comparison are therefore not from the optimal region of the parameter space for rectangular blocks. The model has clearly demonstrated that it is dangerous to generalise from a rectangular block pavement to a dentated block pavement with the same parameters, and presumably therefore each of the common commercial shapes for interlocking blocks could be expected to perform differently.
For practical purposes it is desirable that the pavement can accommodate as much block variation as possible, since unnecessarily frequent replacement of expensive block moulds or use of other close-tolerance quality control techniques is undesirable. A small range of values for standard deviation of blocks was therefore identified within which some, but not all, parameter combinations led to pavement compliance with the current acceptability criteria. Table 1 shows how the acceptable amount of variation, according to the model, relates to block measurement data available to the authors and to the current Australian Standard for allowable variation. The table indicates that the model's recommended level of variation appears to be attainable with current manufacturing technology.
The results reported here compare dentated and rectangular blocks laid up to nibs of nominal dimension (NIB) 1.5mm or 2mm. The nib dimension is a random quantity with the nominal value as its average, and with standard deviation (NSD) 0.1mm or 0.2mm. The performance of the

blocks was investigated for a range of design gap sizes (DG) from 1.5mm to 4.0mm in steps 0.25mm. The actual size of the simulated blocks was also a random quantity, with average length and breadth determined by subtracting the design gap value from a nominal module size, and standard deviation (BSD) 0.1mm, 0.2mm, and 0.3mm. These particular values correspond to 99% of simulated blocks being within $\pm$0.55m, $\pm$1.11mm or $\pm$1.67mm on the block dimension (Australian Standard specifies blocks to be within $\pm$2mm of nominal dimension.

TABLE 1

Standard Deviation of measured block plan dimensions (from 3 moulds)	Model standard deviation for plan dimensions	Standard deviation of measured spacer nib dimension (from 3 moulds)	Model standard deviation for spacer nibs
0.32mm, 0.38mm, 0.37mm	0.22mm, 0.43mm, 0.65mm	0.12mm, 0.24mm, 0.09mm	0.1mm, 0.2mm

The results displayed in Figures 6(a) and 6(b) are samples of the pattern of over-sized gaps typically found in simulated pavements with rectangular and dentated blocks. The most important feature, particularly for the dentated block model, appears to be extreme patchiness. This is important to bear in mind when considering measures of overall pavement performance such as percentage of gaps 4mm-5mm. The practical requirement is usually that this should be small (under 5% of all gaps) locally (say, in any 3m x 3m square); the simulations show that a pavement may readily satisfy this requirement over the whole area, but fail to do so when smaller subareas are considered.

Figures 7(a-b) and 8(a-b) display, for dentated and rectangular blocks respectively, the relationship between total number of gaps over 5mm, design gap and block standard deviation for two different nib mean dimensions. The Figures show that having nibs thicker than the design gap size is undesirable for dentated blocks, that design gaps between 2.5mm-3.5mm lead to relatively better performance, and that nibs 1.5mm in dimension lead to better performance than 2mm nibs.

The Figures also show that rectangular blocks have different performance characteristics. Whereas the dentated blocks perform extremely poorly when nominal nib dimension is the same as or larger than the design gap, the rectangular block pavement is unaffected. The range of design gaps for which rectangular blocks achieve a satisfactory pavement is quite different to that for dentated blocks, and when laid up to nibs the effect of increasing the variability of blocks and of nibs is greater than it is for dentated blocks. A region of superior performance for rectangular blocks can be shown to occur when the blocks are laid with a fixed target gap. Laying such blocks relatively loosely, with fairly small standard deviation, is a successful strategy; however, this end cannot be achieved simply by equipping the blocks with large nibs.

Figures 9(a) and 9(b) show the regions of direct influence of a specific block in areas of rectangular and dentated paving. The dentated block directly influences every block subsequently laid, whereas the rectangular block has limited zones of influence. This is further evidence that different block shapes have different performance characteristics.

6. Conclusions

The study reported here has shown that it is possible to model the gaps between variably dimensioned, differently shaped block pavers, with or without nibs and under different boundary conditions and laying methods. The results obtained from the model are a reasonable representation of block performance observed in practice. The factorial experimentation process has shown that the interaction between design features (the designer's selection of a value for design gap and nib dimension), manufacturing tolerances (the standard deviation allowable on manufactured block and nib) and laying practice (for example, nib dimension dictating whether blocks are laid tight or loose relative to their design gap) must be understood for optimal

performance.
The model has shown the generated pattern of the gaps to be highly shape-dependent. Thus an empirical rule for successfully laying one shape of block (lay rectangles slightly loosely, aiming for a fixed size of gap between them) may be disastrous for another shape (laying the particular dentated shape loosely made the blocks wedge themselves apart).
It follows that it is essential for a block designer to determine desirable parameter dimension mean values, an achievable amount of variability for block and nib dimensions, and a desirable proportion (design gap) given the particular gap size criteria being imposed.
The hypothetical dentated shape with which we have been working appears to be inherently unstable, in the sense that the gap performance gets worse over larger areas, so that a set of parameters which will produce an apparently perfect pavement 12 metres wide, may no longer be satisfactory over 50 metres, let alone the areas that arise in some airport paving projects. It is appreciated that large areas have been successfully laid, but the model indicates that such achievements may have well have been influenced by a substantial degree of chance and the application of craft knowledge.
The model suggests strongly that, for the dentated shapes, trying to address the practical laying problem of too many, too large gaps by relaxing the limit on the maximum allowable gaps, or the proportion of over-sized gaps, will not ensure that a large area can be satisfactorily paved. Unless the other aspects are properly designed and controlled, the pavement will eventually overtake any specified limit.
The model prescriptions may cause some concern amongst manufacturers due to the indicated need to impose limits on the manufactured variation of blocks and nibs. However, the model shows that large areas can be satisfactorily paved, using combinations of parameters which appear to be achieveable (albeit with some difficulty) with the manufacturing technology understood by the authors to be available. Such data as is available to the authors about more and less successful large scale pavements is consistent with the model predictions in this respect.

The authors wish to acknowledge the support of Mount Isa Mines Holdings Ltd and the Queensland University of Technology throughout this project, and for their approval to publish this paper.

7. References

[1] Clifford, J.M Segmental block pavements. Optimising the joint width and joint material. Proceedings of Second In. Conference on Concrete Block Paving, Delft Uni. Tech, 1984 p.238-244
[2] Lilley, A.A Size and block shape - Do they Matter? Manuscript submitted to 2nd Int. Workshop on Concrete Block Paving, Oslo 1994
[3] Shackel, B. Design and Construction of Interlocking Concrete Block Pavements. Elsevier Science, London 1990
[4] Lilley, A.A A Handbook of Segmental Paving. E & F.N Spon, London 1991

Address for Correspondence:
Dr M.S Mackisack
School of Mathematics
Queensland University of Technology
G.P.O Box 2434
Brisbane Q 4001
AUSTRALIA

FAX: +61 7 864 2310

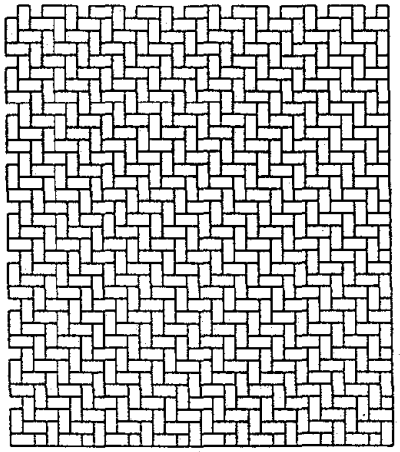


Figure 1.
Herringbone Bond

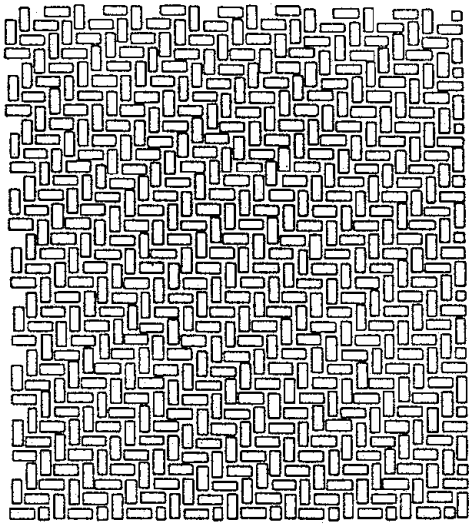


Figure 2.
Gaps between Blocks

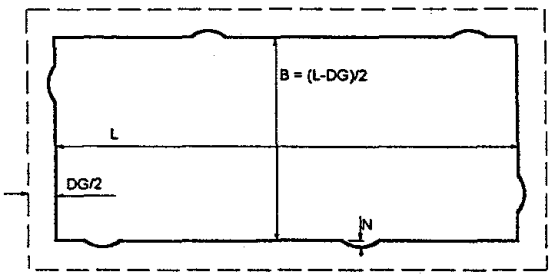


Figure 3.
Rectangular Block Model

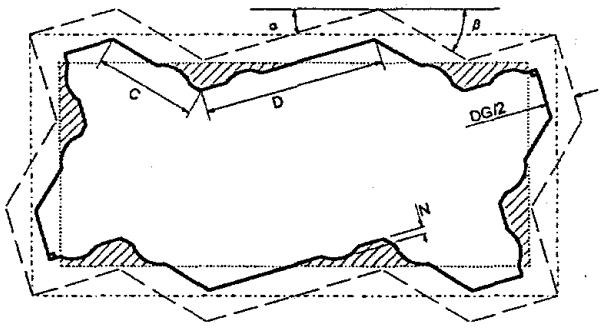
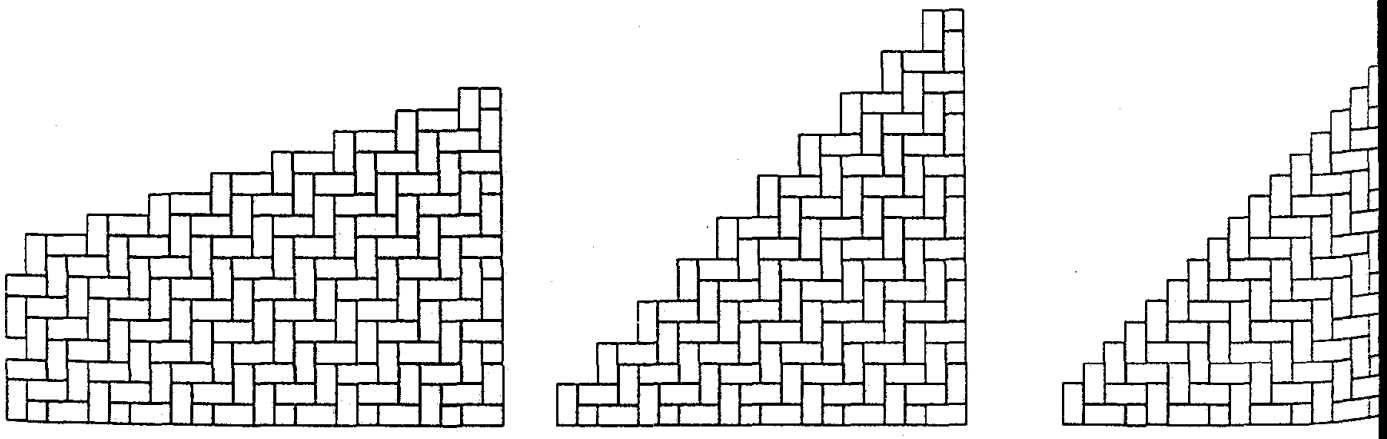


Figure 4.
Dentated Block Model



Method 31 Method 45 Method FB

Figure 5. Block Laying Sequences

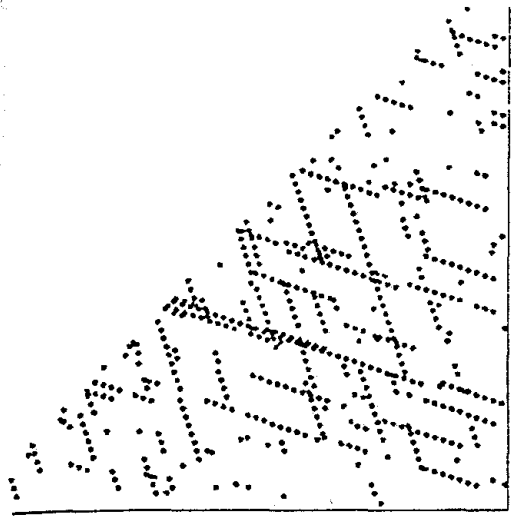


Figure 6(a).
Pattern of oversize gaps -
Rectangular blocks

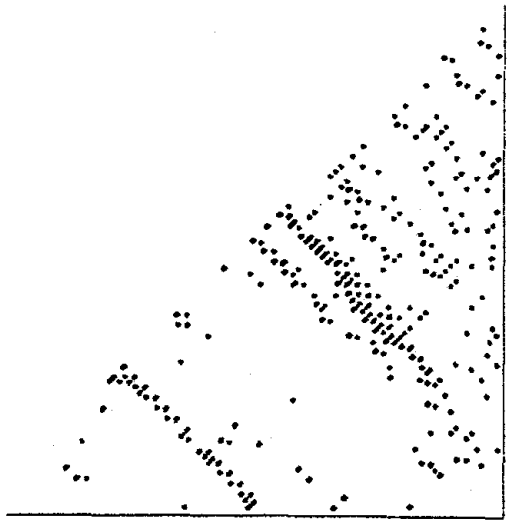


Figure 6(b).
Pattern of oversize gaps -
Dentated blocks

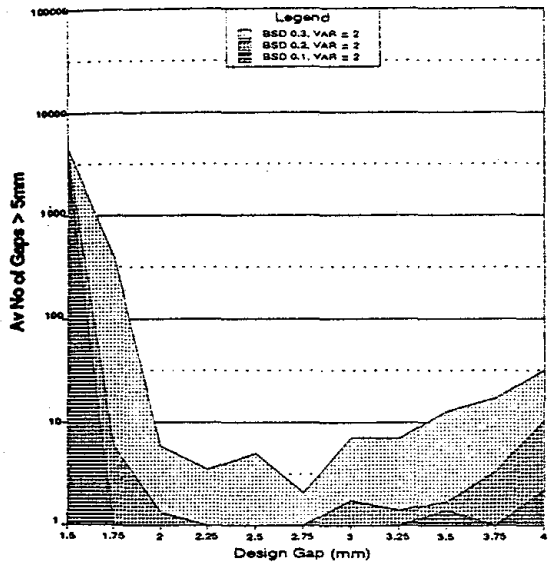


Figure 7(a).
Dentated blocks
Nibs = 1.5mm, by Block Std Dev (BSD)

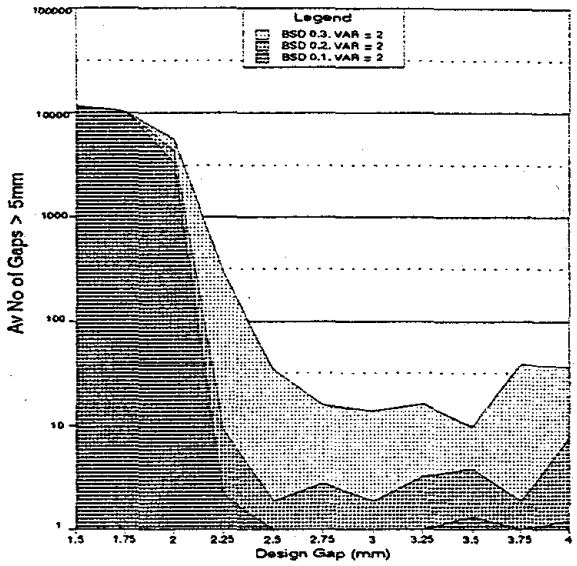


Figure 7(b).
Dentated blocks
Nibs = 2.0mm, by Block Std Dev (BSD)

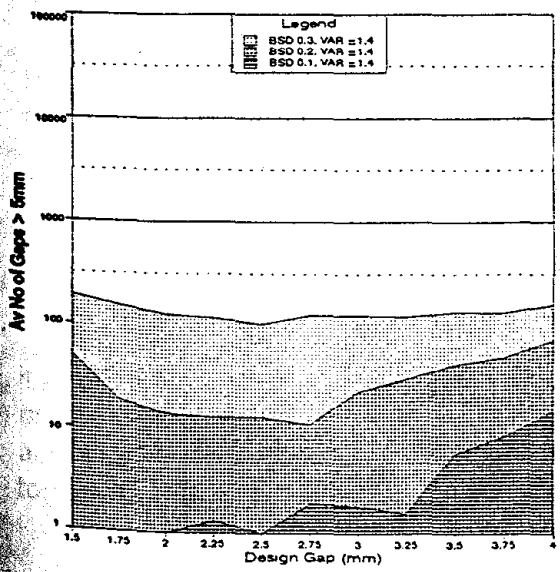


Figure 8(a).
Rectangular blocks
Nibs = 1.5mm, by Block Std Dev (BSD)

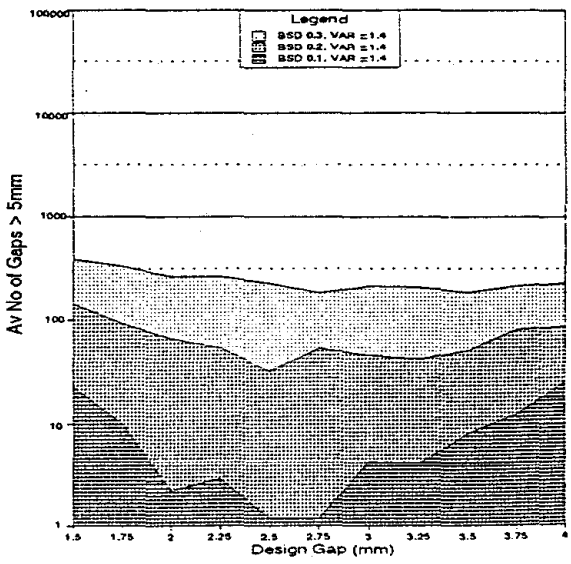


Figure 8(b).
Rectangular blocks
Nibs = 2.0mm, by Block Std Dev (BSD)

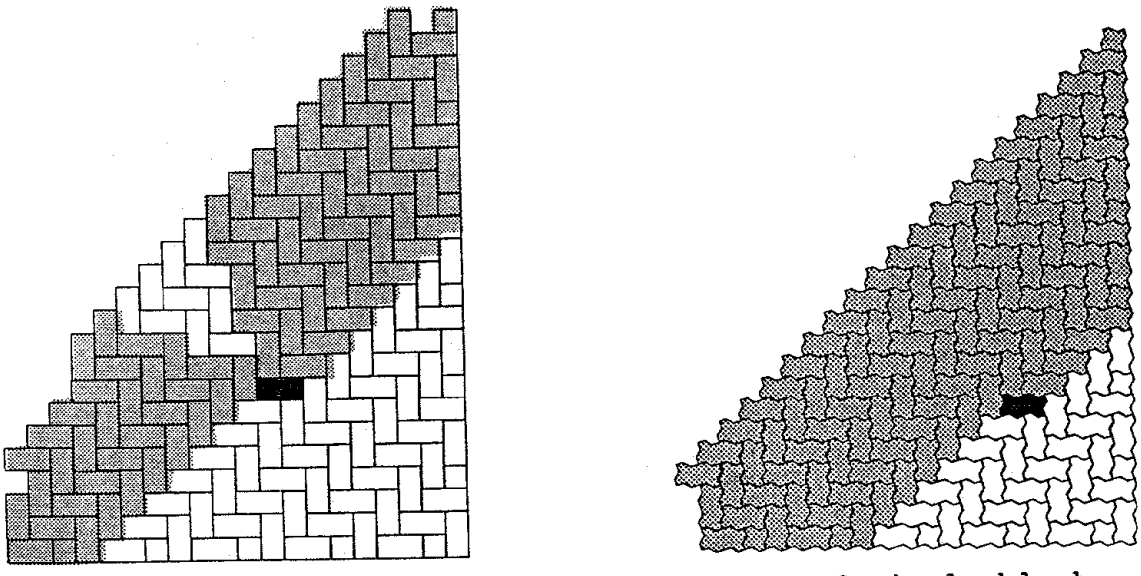


Figure 9. Regions of direct influence of single block